Neutron Sources Globally

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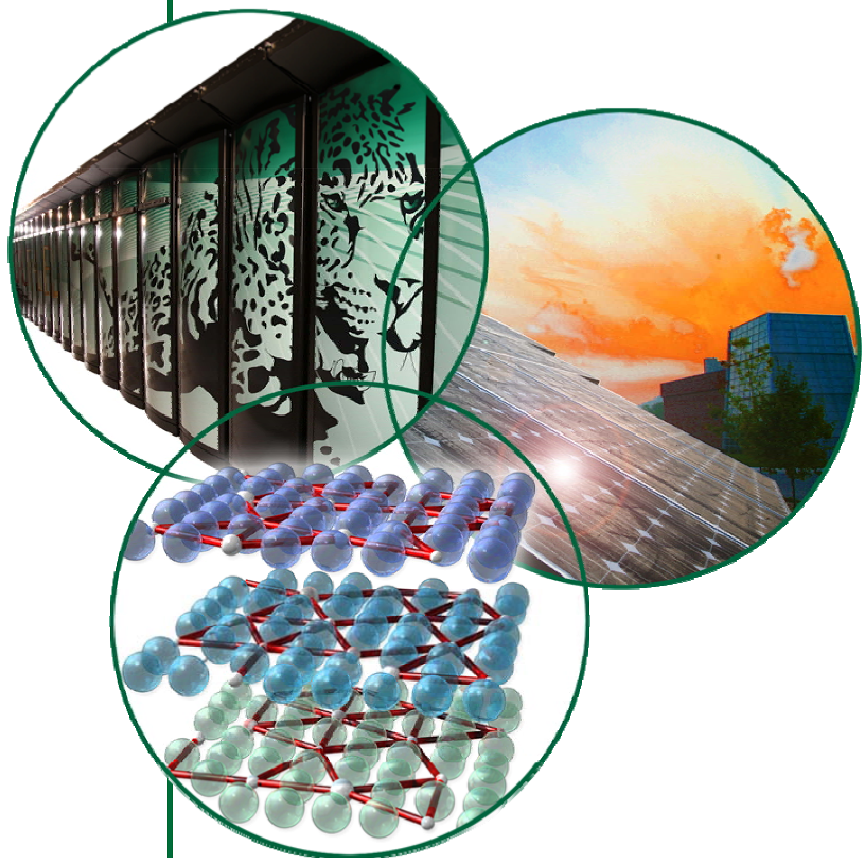
Neutron Source Development Group Leader

Spallation Neutron Source

International Workshop on Accelerator-Driven Sub-Critical Systems & Thorium Utilization

Blacksburg, VA

September 27-29, 2010



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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Neutron sources…

general term referring to a variety of devices that emit neutrons, irrespective of the mechanism used to produce the neutrons

- Small
  - Spontaneous fission, (α,n), (γ,n), n generators
- Medium
  - Plasma focus/pinch devices, light ion accelerators, photoneutron/photofission systems
- Large
  - Reactors, fusion devices (NIF, JET, etc.), spallation sources

We'll focus on large facilities

What are the needs?

- From a target point of view
  - High beam power capability
  - High reliability
  - High availability
  - Good conversion efficiency (n/p)
  - Low absorption cross section
  - Minimize R&D
- Spallation targets a[illegible]gned for a variety of applications
  - High b[illegible]s (peak flux)
    - [illegible]ARC, ISIS
  - [illegible]verage brightness (flux over a large area)
    - APT, MTS, UCN sources

Source design should be customized for the application

Managed by UT-Battelle
for the U.S. Department of Energy

Focus on some accelerator neutron sources

- High-power
  - LAMPF/LANSCE
    - APT project
  - SINQ/MegaPIE
  - ESS/SNS/JPARC
  - Eurisol
- ADS specific
  - RACE

What has occurred over the last 15 years that we can use?

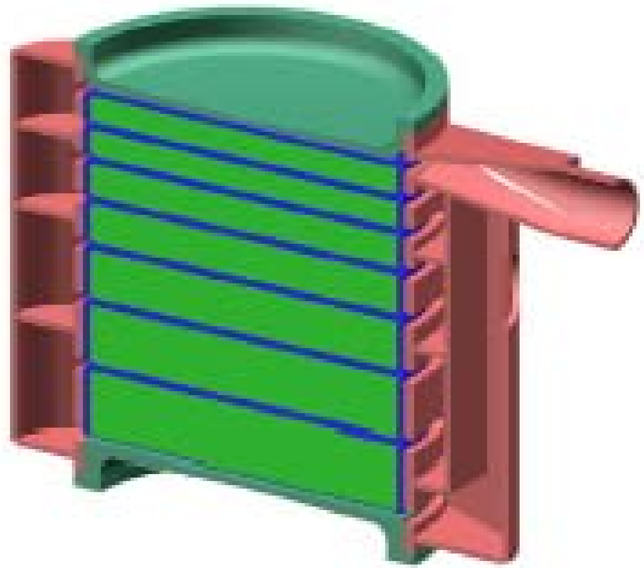
- Basic source neutronics

Los Alamos Neutron Science Center (or Los Alamos Meson Physics Facility)

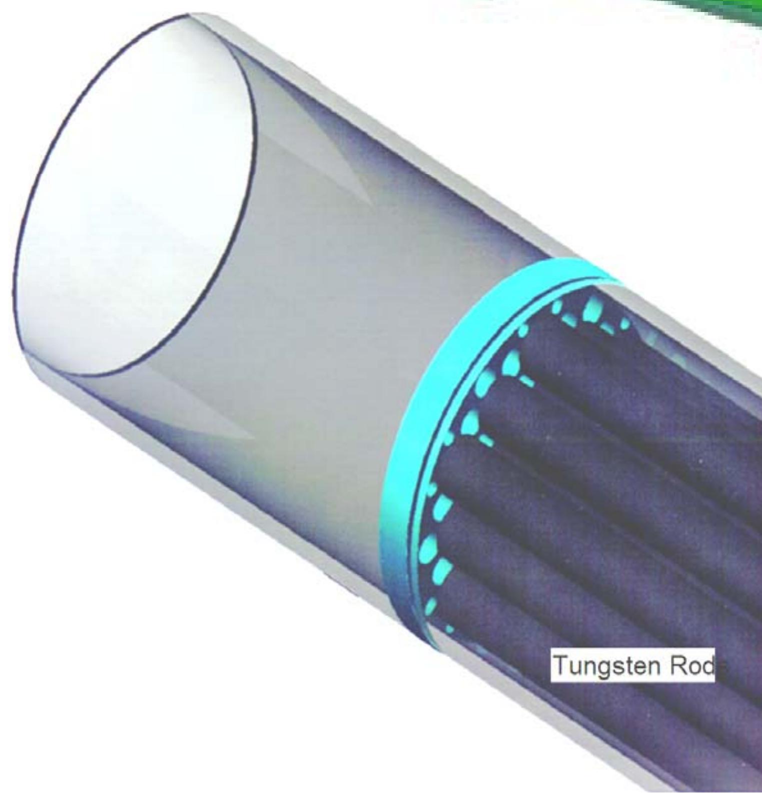
- 800-Mev, nominally 1 mA proton beam
- 800-MeV reached in 1972
- Three beams: H+, H-, p-
- Highest power proton linac for many years
- Contributions:
  - High power capability
  - Solid target technology
  - Radiation damage to materials
  - Code verification & validation

Solid (W) targets at LANL

- Plate targets (~14 µA/cm^2)
  - Same peak current density as SNS



- Rod targets (~70 µA/cm^2)
  - Bare
  - Clad

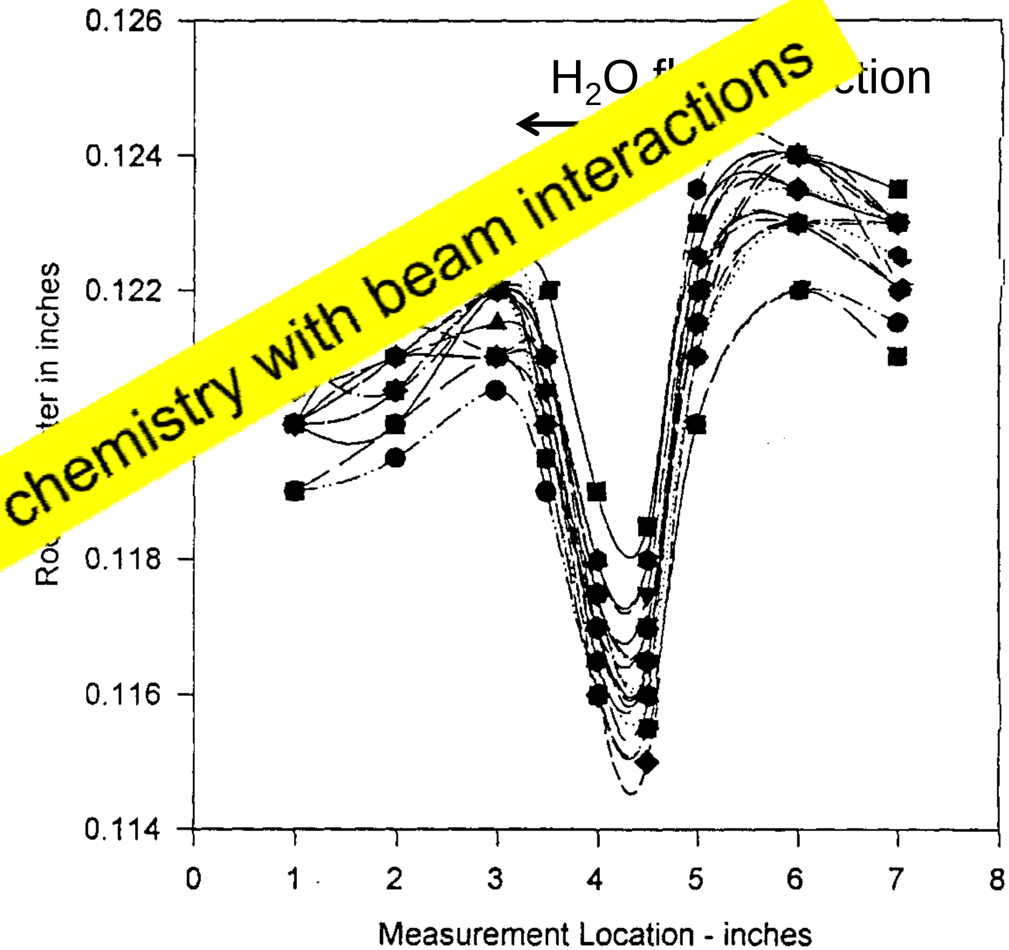


LANL contributions from S. Maloy

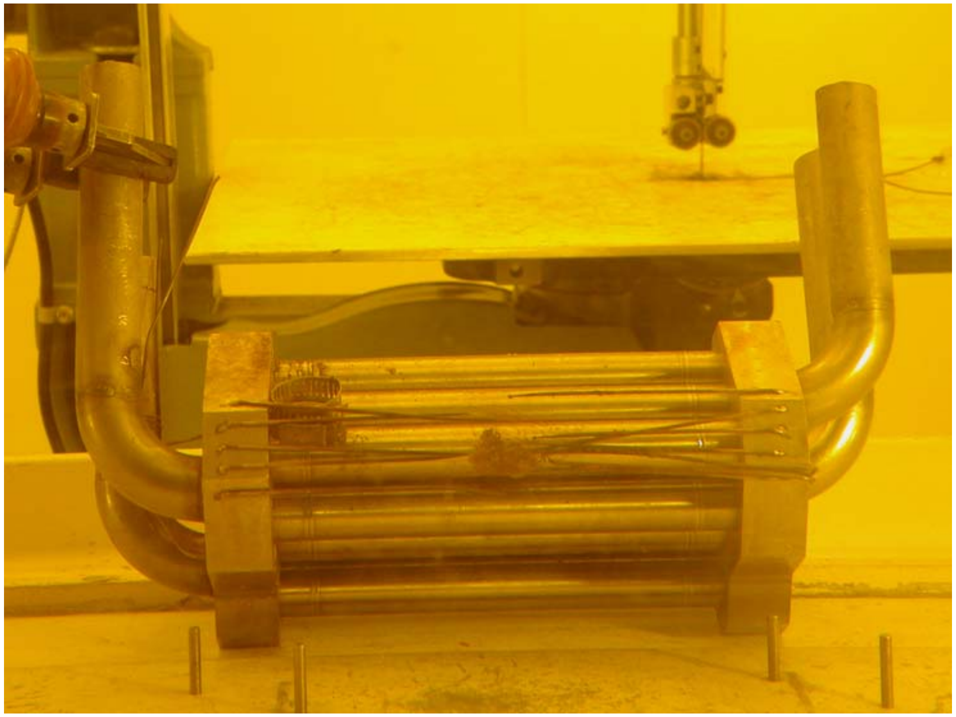
Decrease in Diameter of Bare Tungsten Rods Confirmed Tungsten Corrosion Rate

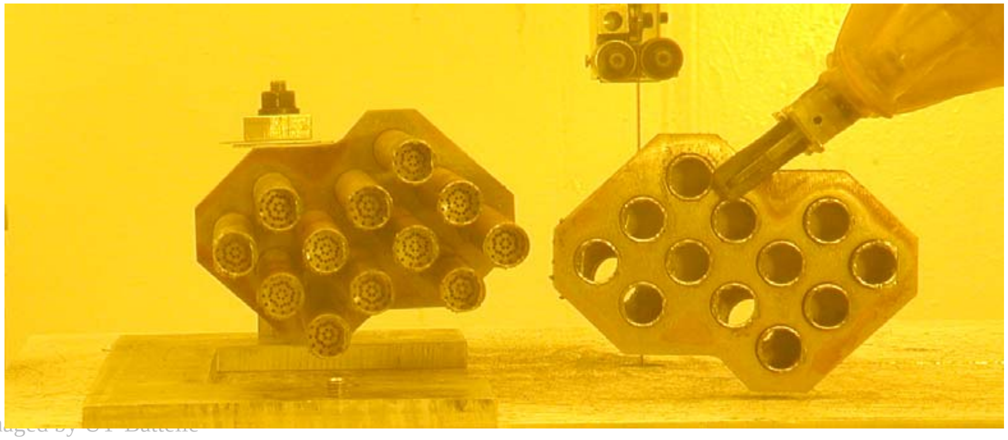
- Capsule irradiated for 2 months in 800 MeV, 1 mA proton beam (~$2x10^{21}$ p/cm^2)
- Measured the diameter of all 19 tungsten rods in the leading rod bundle
- The loss of tungsten on rods scaled with Gaussian beam shape
- Implied corrosion rate of ~1 mm /year
- Measured Helium concentration of ~740 appm

Demonstrated the complex chemistry with beam interactions



Removal of Tungsten Neutron Source After Irradiation

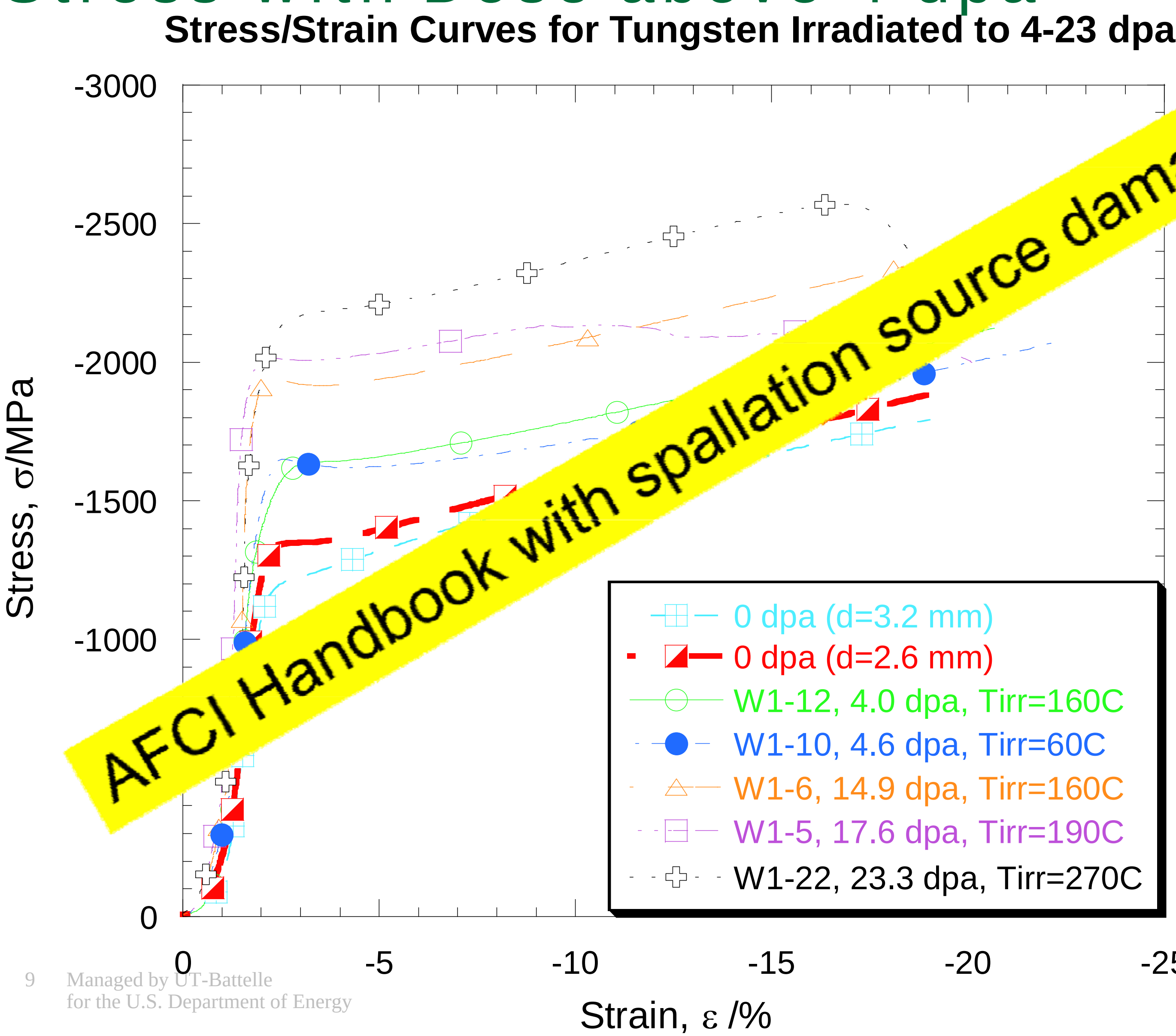


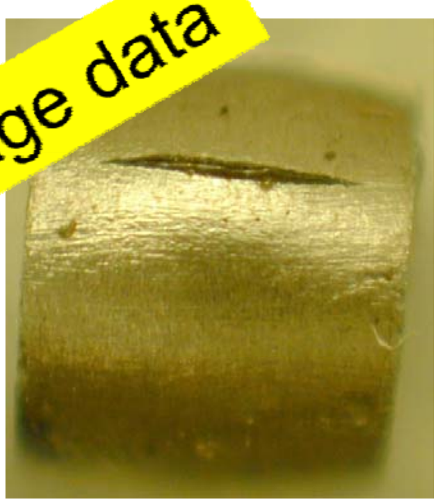


- Clad Tungsten Source cut from Insert and transported to CMR Hot Cells
- Peak proton density ~70 μA/cm^2
- Helium leak test performed in hot cells showed clad rods still leak tight after irradiation
- Discoloration on outside surface due to high nitric acid irradiation environment

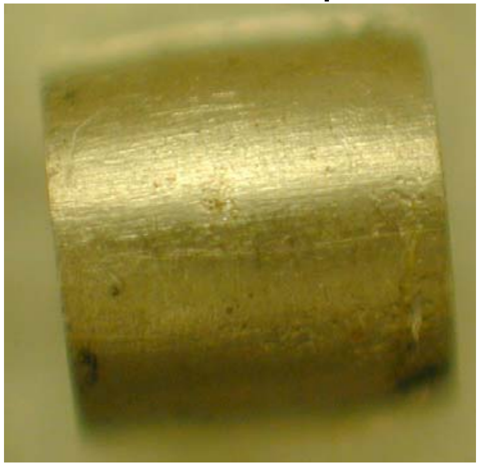
OAK RIDGE National Laboratory

Compression Stress/Strain Results for Irradiated Tungsten Show Increase in Yield Stress with Dose above 4 dpa





3.2 dpa

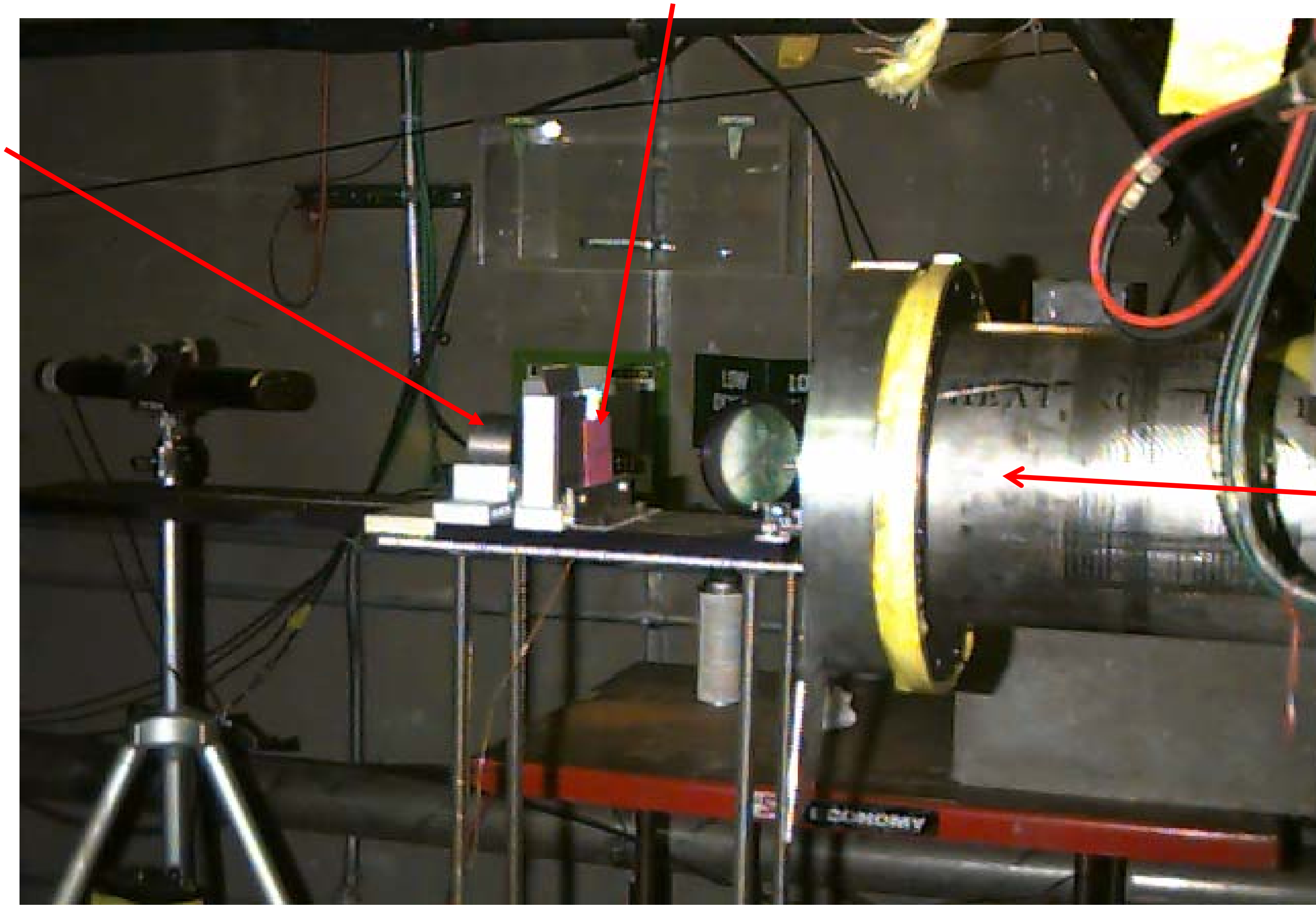


0 dpa

Code V&V: Decay heat experiment

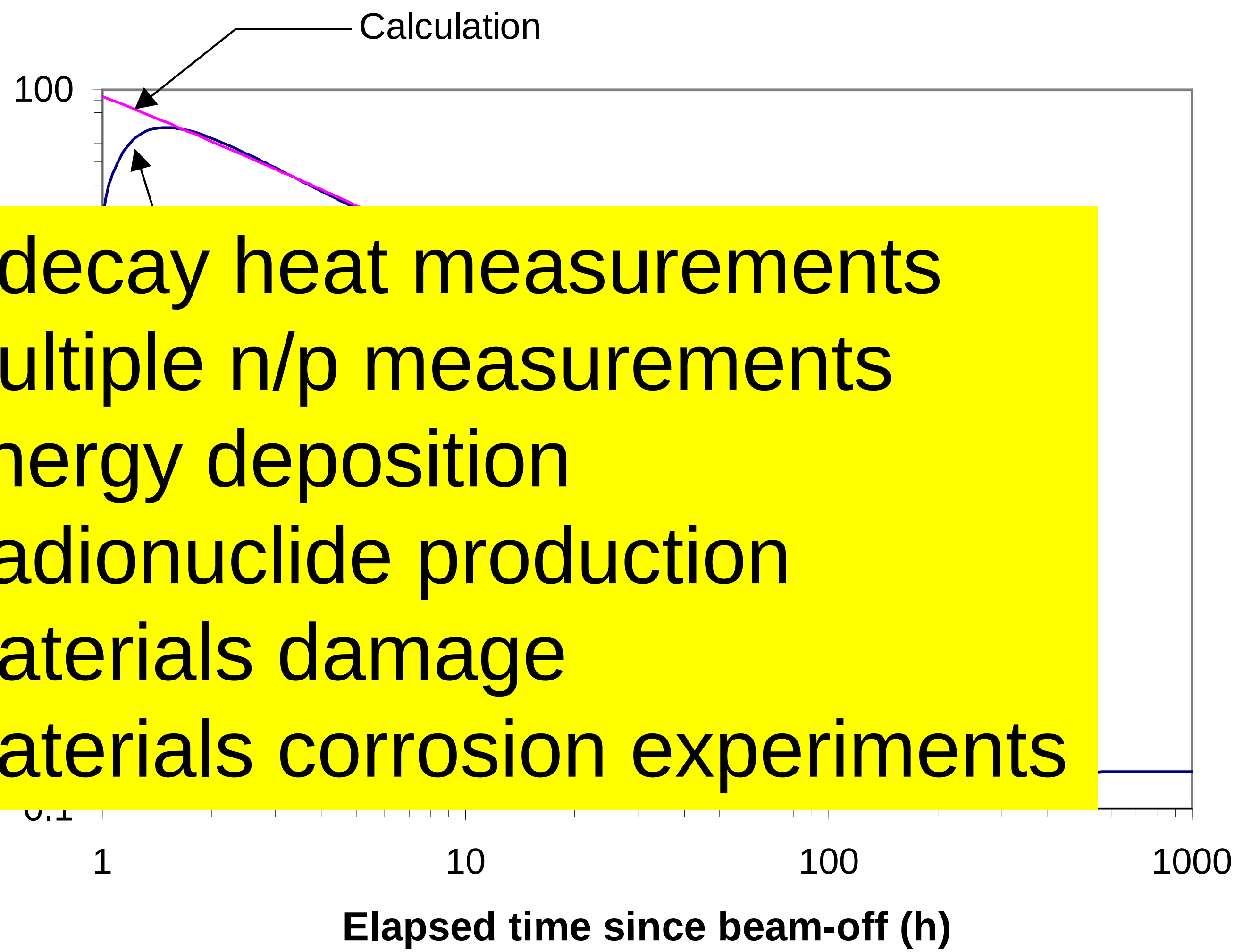
Phoshpor

W target



p

Calculated and measured decay heat



2 decay heat measurements
Multiple n/p measurements
Energy deposition
Radionuclide production
Materials damage
Materials corrosion experiments

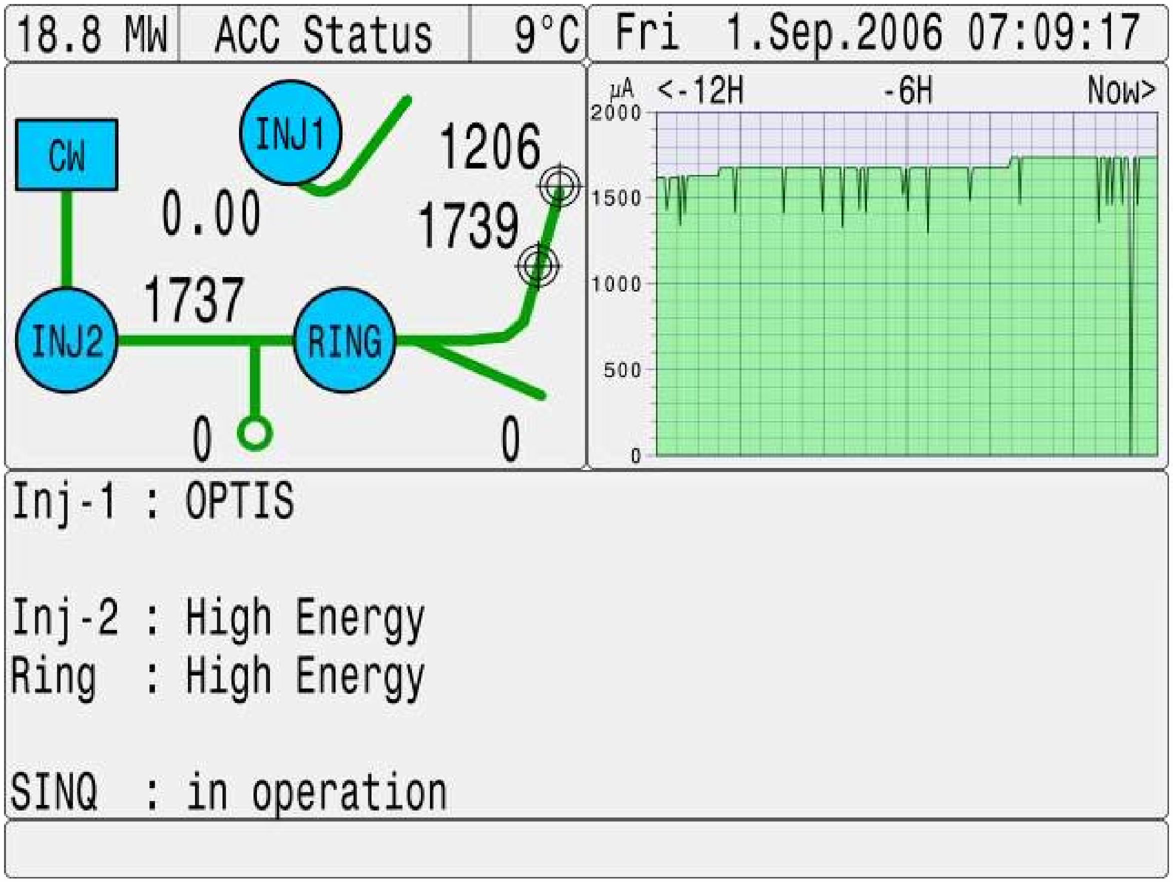
SINQ (Paul Scherrer Institut)

- ~570-MeV protons incident on a solid target, ~1.2 MW
- Continuous source
- Vertical beam insertion upward
- Contributions:
  - Continuous operation with high reliability
  - High-power liquid metal target demonstration
  - Radiochemistry of liquid metal targets
  - Beam on target imaging
  - Materials irradiation data

SINQ contributions from M. Wohlmuther, J. Neuhausen

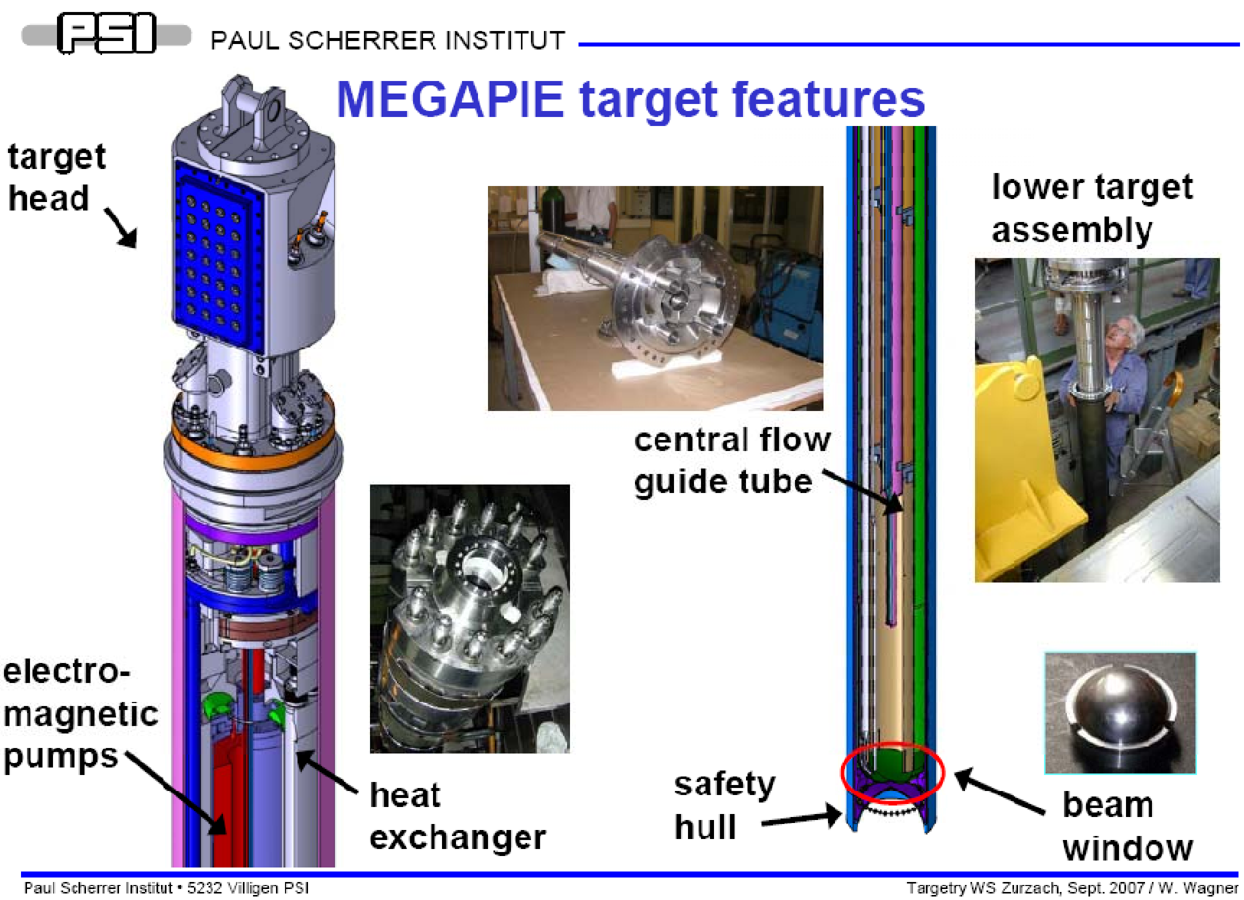
High reliability operations

- During MegaPIE startup
- One significant trip in 12 hours (more than ~1 minute)
- Probably good enough for a transmutation demonstration

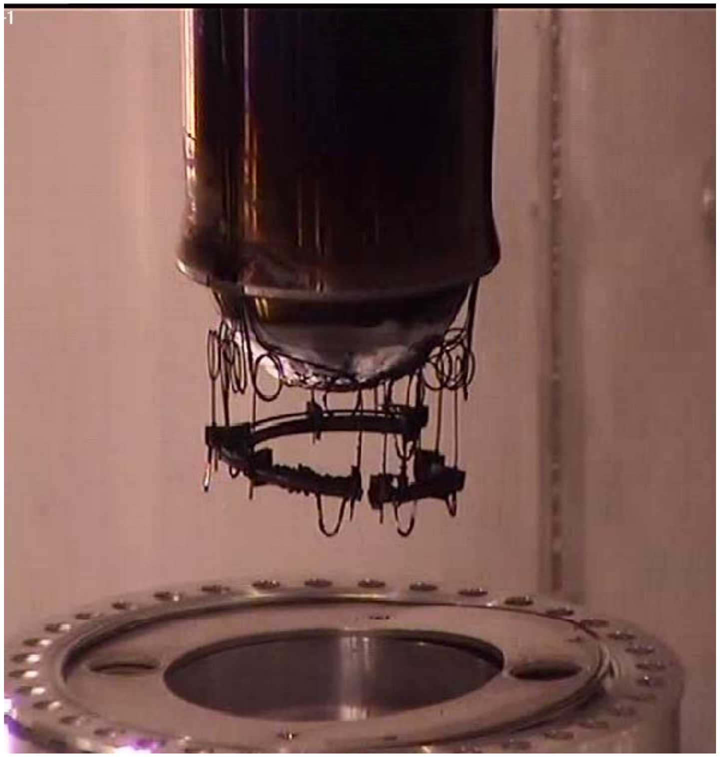


MegaPIE target at SINQ

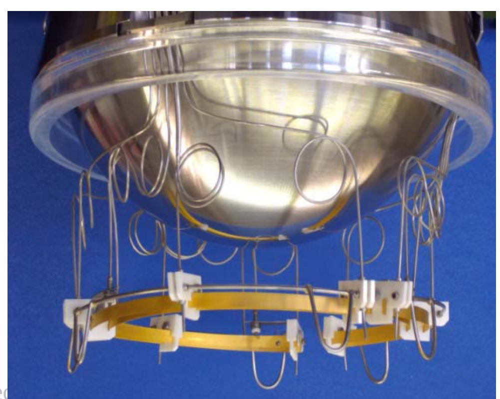
- LBE target installed in existing solid target location
- Full process, from design to safety evaluation, from licensing to high-power operations
- Operated from August 14, 2006 to the end of 2006



Target disassembly



After



Before

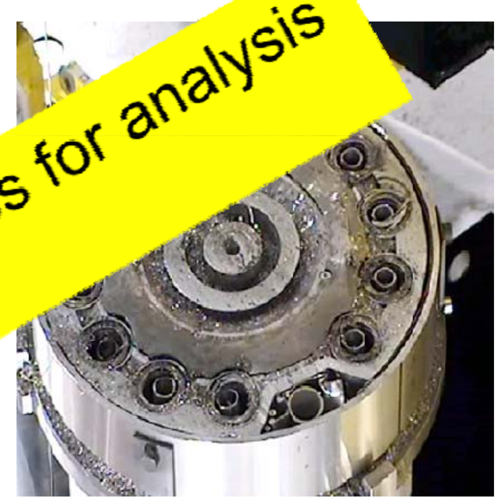
- The aluminum safety hull was removed July 2009
- Picture: The “remains” of the Leak Detector (LD)
- Black smut was deposited on one side of the LD
- The beam entrance window region looked whitish/lucent

Samples for analysis

TC3

H06

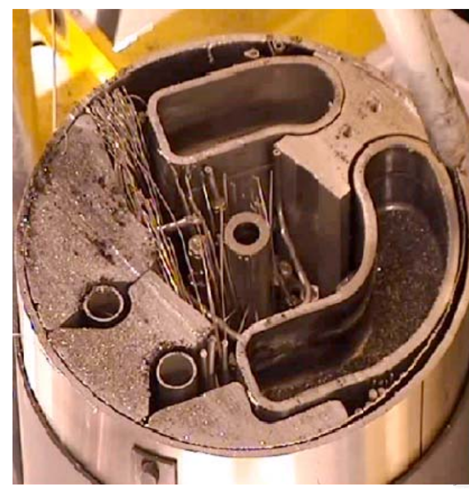
H0



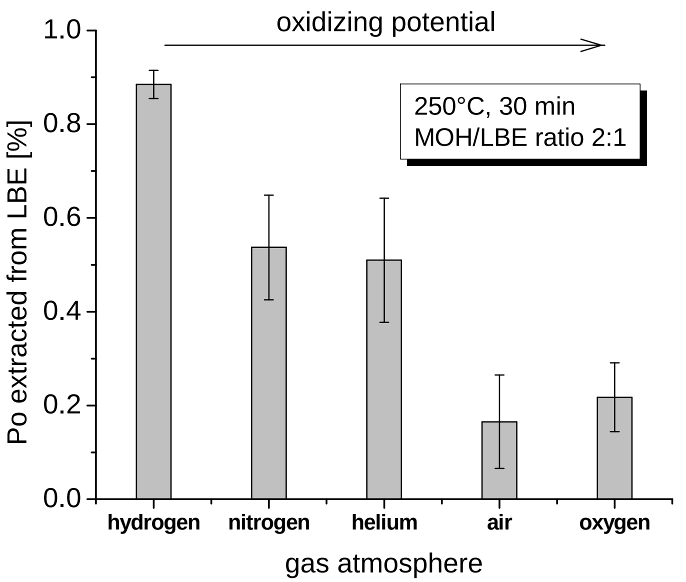
MegaPIE has produced over 1,000 samples for analysis
PIE starts in 2011

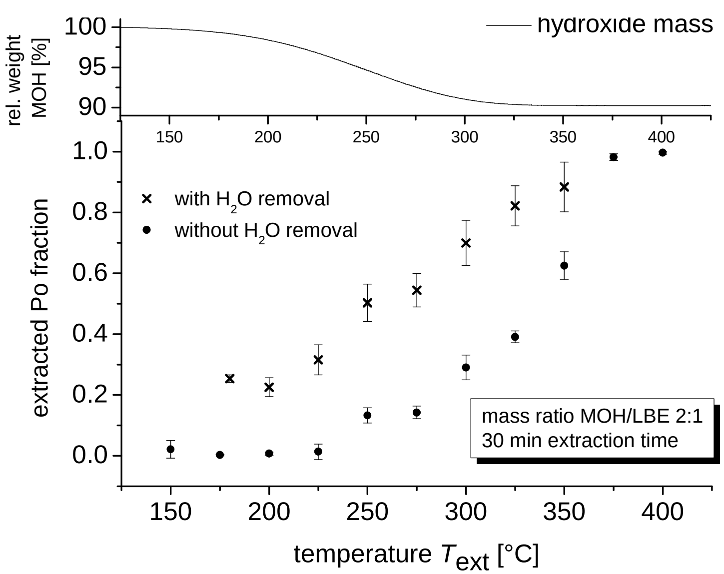
H08

H09

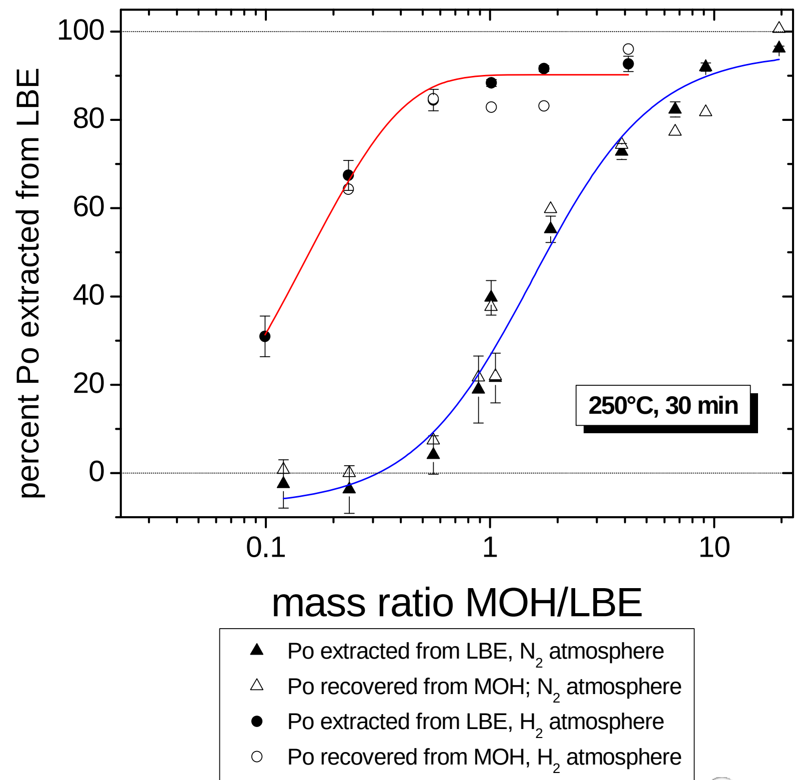


Po extraction from LBE: Results



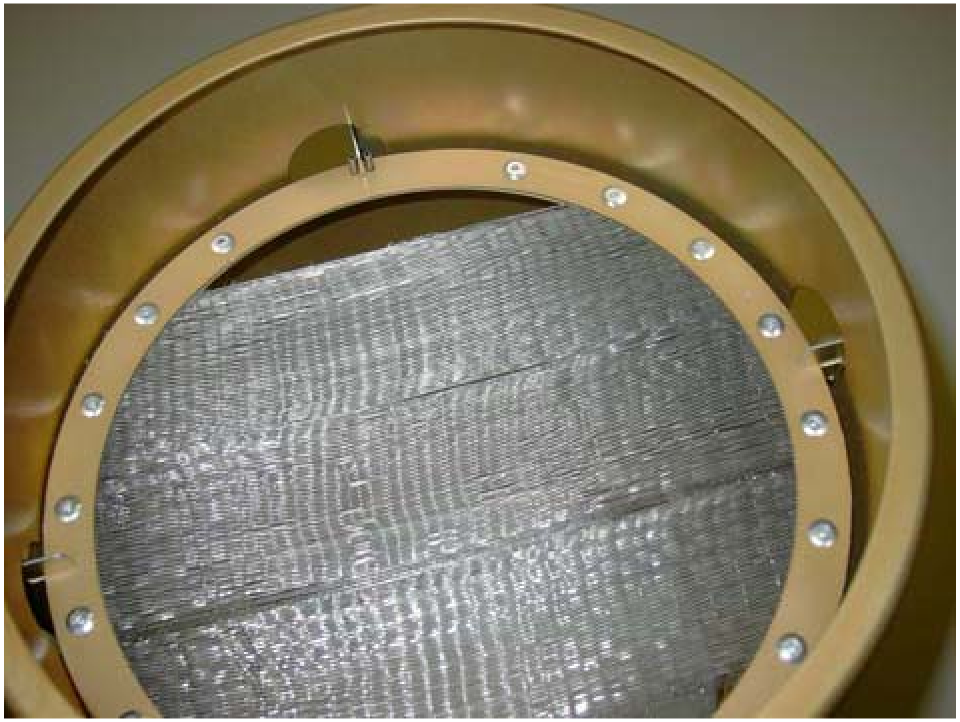


- Influence of gas plenum
- Temperature curves
- Influence of water content of (Na,K)OH
- Relative amounts of LBE/MOH



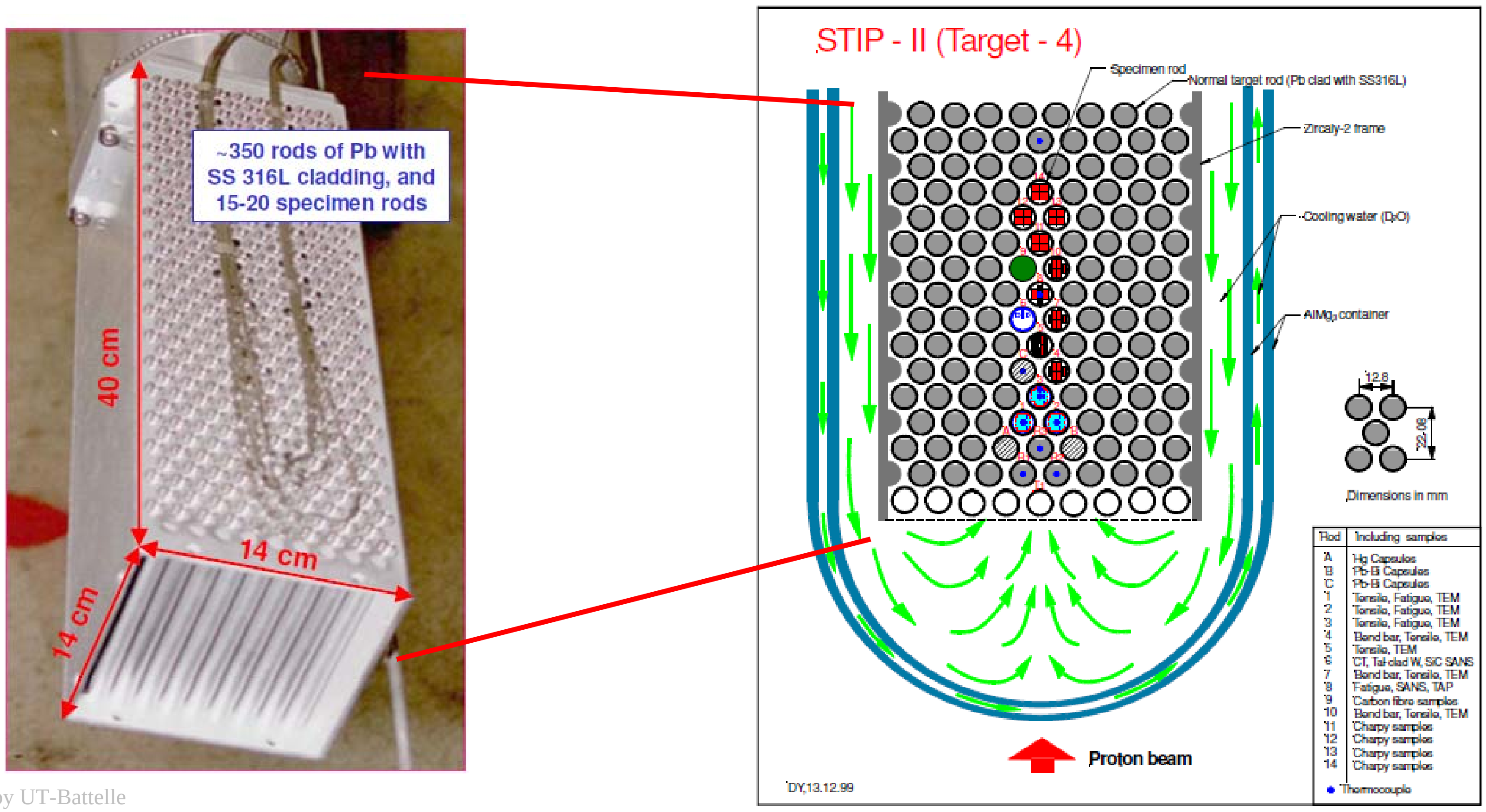
Beam on target monitoring: VIMOS

- Tungsten mesh through which the beam passes
- Beam profile monitored via a camera and optics
- Reliable operation since 2004
- Important part of the safety case and determining target lifetime



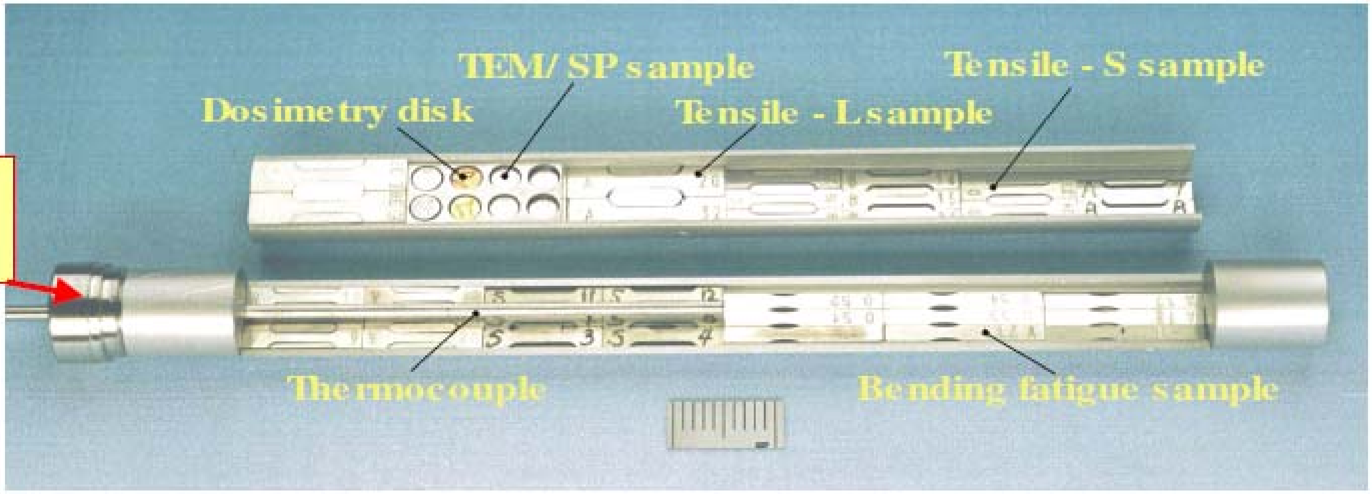
STIP Irradiation Series

- Five campaigns, thousands of samples
- SINQ target rods replaced by materials samples



Typical STIP samples

130 mm length
10.8 mm diameter

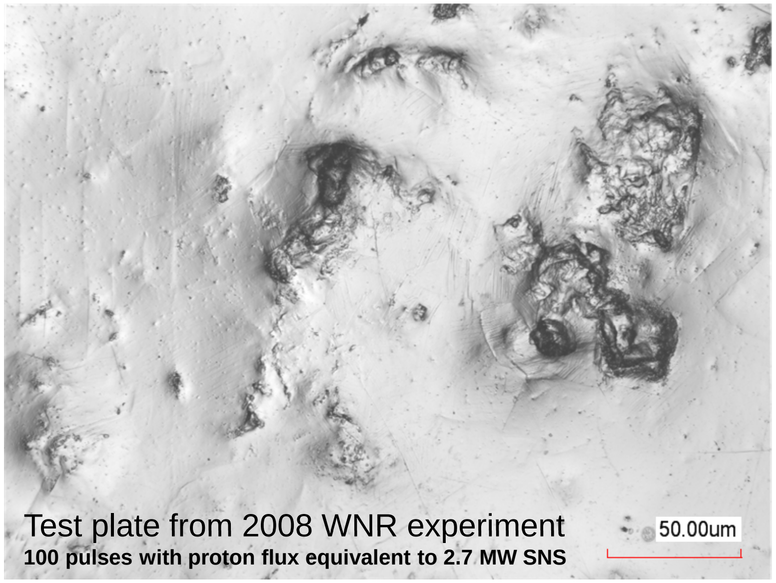


Spallation Neutron Source (ESS, J-PARC)

- Three spallation sources designed in the same timeframe
  - ESS was first, but not funded
  - SNS was based largely on the ESS concept, then advanced
  - J-PARC was ~18 months after SNS
- SNS is nominally 1-GeV, 1.4 MW
  - PUP to 1.3 GeV, 1.8 MW in 2016
- Contributions:
  - Liquid metal target development
  - Solid rotating target development
  - Beam on target imaging
  - PIE data

The SNS target is mercury circulating inside a stainless steel vessel at 24 liters/second

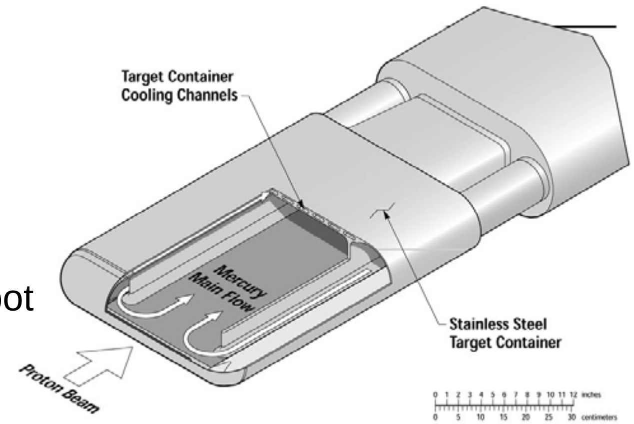
- System is capable of 1.4 MW beam power on target
- Target module must be replaced periodically due to embrittlement of the steel
- Beam induced cavitation damage might limit target module life more severely than radiation damage at high beam power

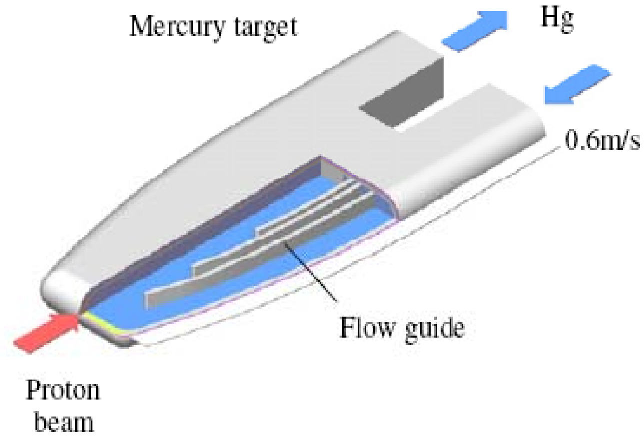


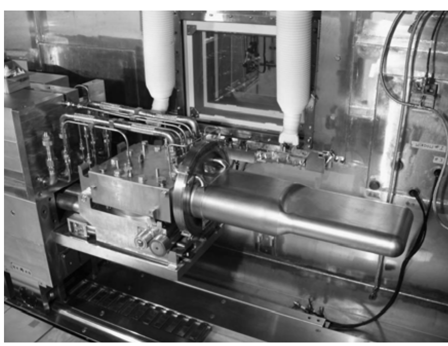
Mercury Targets - SNS and JSNS

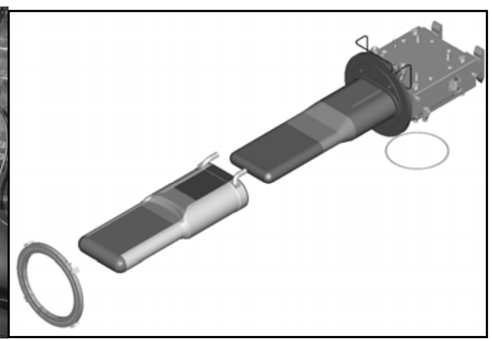
SNS Parameters

316L mercury vessel and water shroud
1 MW design
200 mm x 70 mm beam spot
0.125 A/m2 peak current density @ 1 MW
24 l/s mercury flow

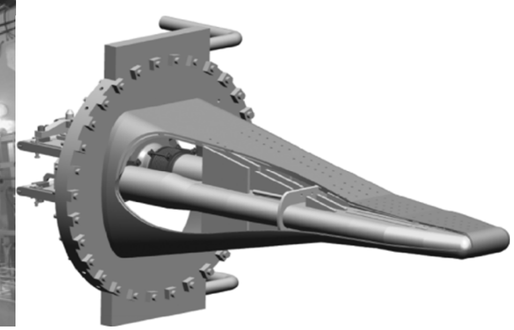








SNS

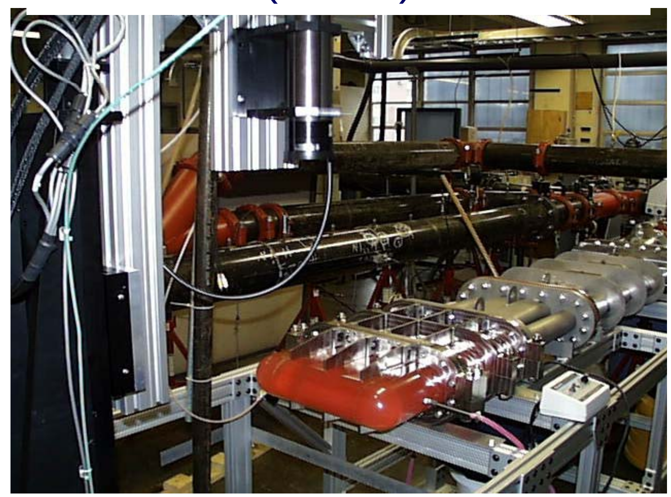


JSNS

SNS Target Development- typical component development

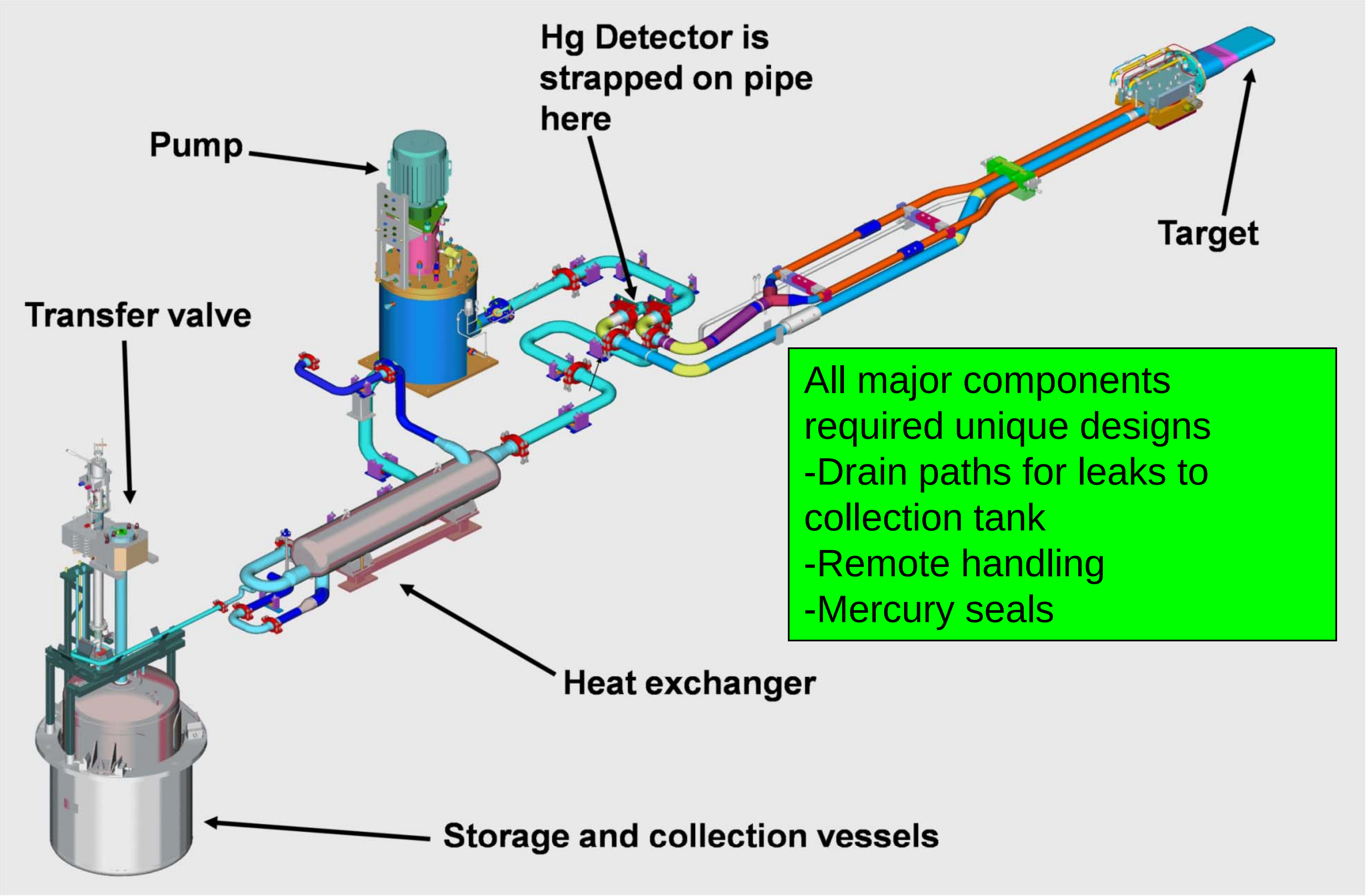
Mercury Thermal Hydraulic Loop (MTHL)

Water Thermal Hydraulic Loop (WTHL)



Target Test Facility (TTF)

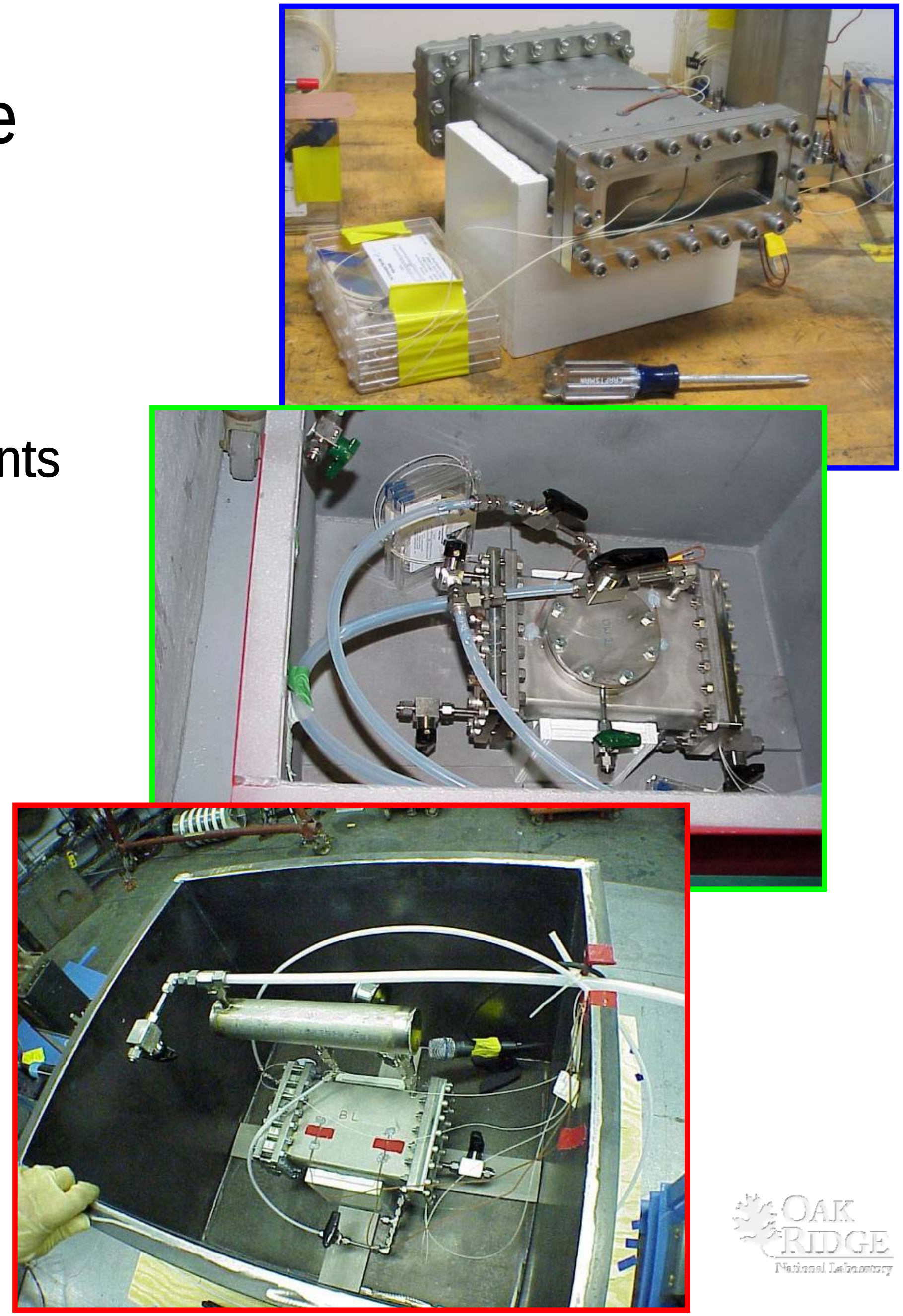
SNS Mercury System Layout



All major components required unique designs
-Drain paths for leaks to collection tank
-Remote handling
-Mercury seals

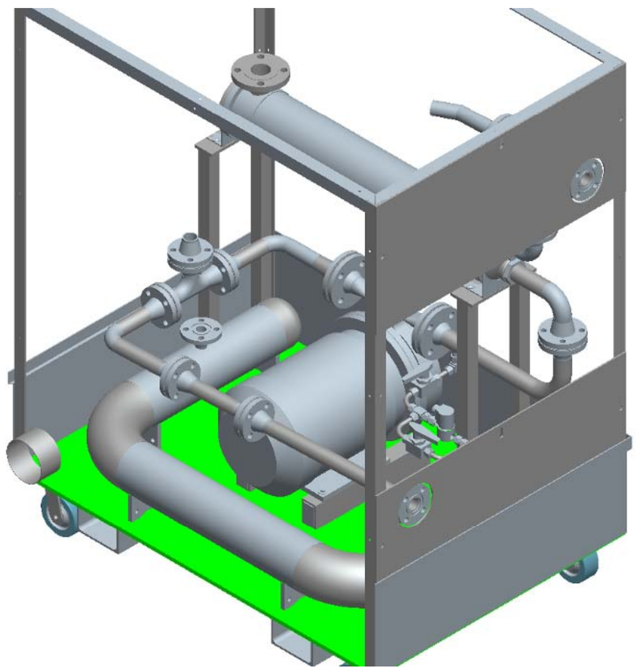
In-beam testing at WNR

- Since 2001, 4 in-beam damage test campaigns have been conducted at the WNR test investigating:
  - Vessel materials & hardening treatments
  - Beam intensity
  - Pulse numbers (1000 maximum)
  - Target geometry & cooling channels
  - Mercury flow
  - Small gas bubble mitigation
  - Gas wall mitigation
  - Lead bismuth

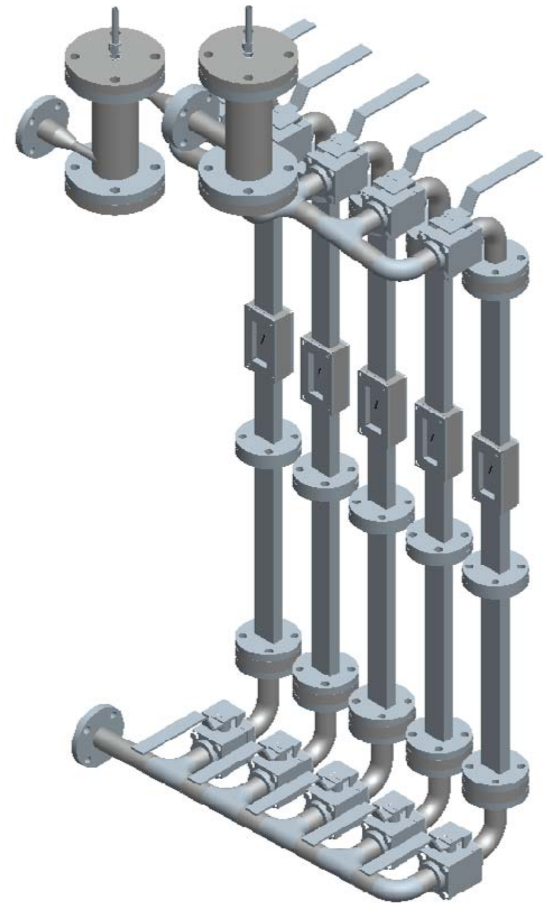


Next WNR Hg target experiment is planned for 2011

- This will investigate small gas bubble mitigation with improved bubblers
- Flowing mercury system required
- Will be done in close collaboration with JPARC team



Pump system



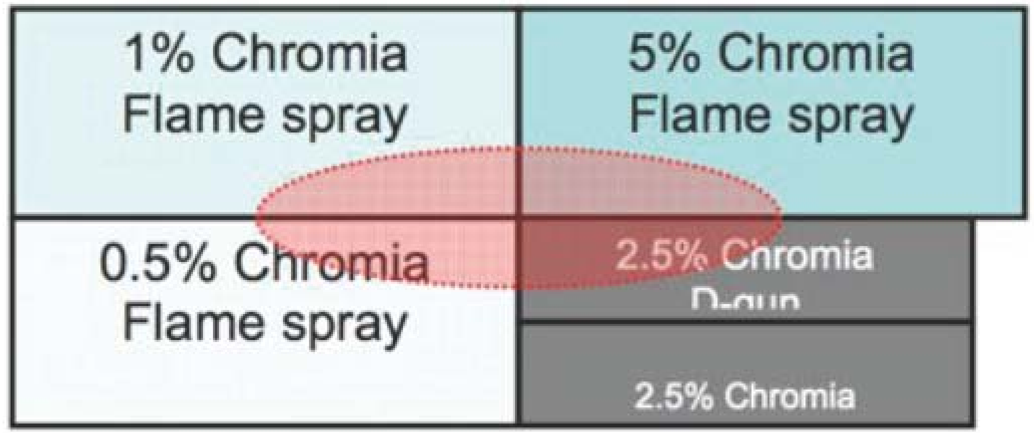
Bubblers & damage test plates

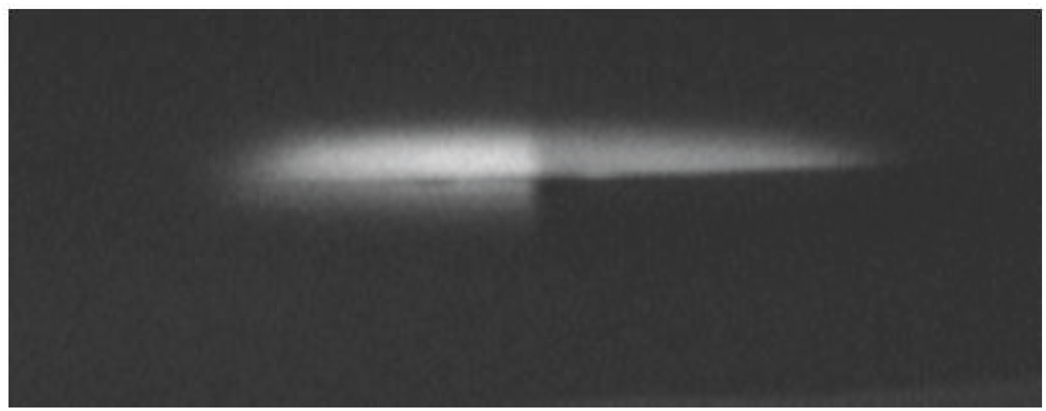
Solid rotating target development

- Designed for a 1.3 GeV, 3 MW proton beam
- Tungsten target with steel support
  - 1.2 m diameter
- Mockup built and tested for over 1,000 hours of operation
  - lifetime >5 years

SNS target imaging system

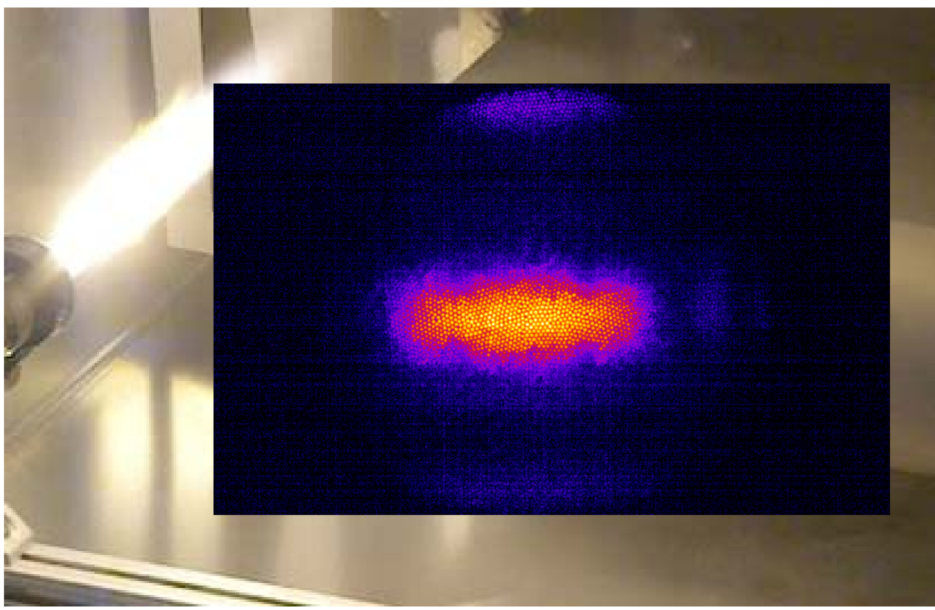
- Based on flame sprayed coatings
- Essentially beam phosphors sprayed onto the target vessel
- Tests at WNR gave reasonable feedback for Chromia doped Alumina

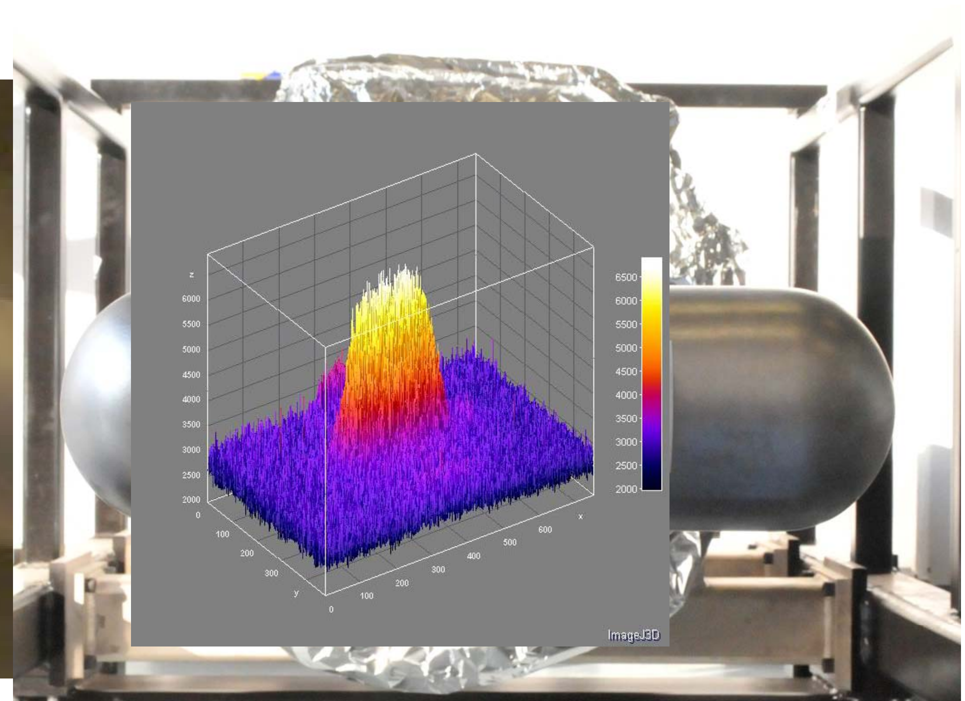




SNS target imaging system (2)

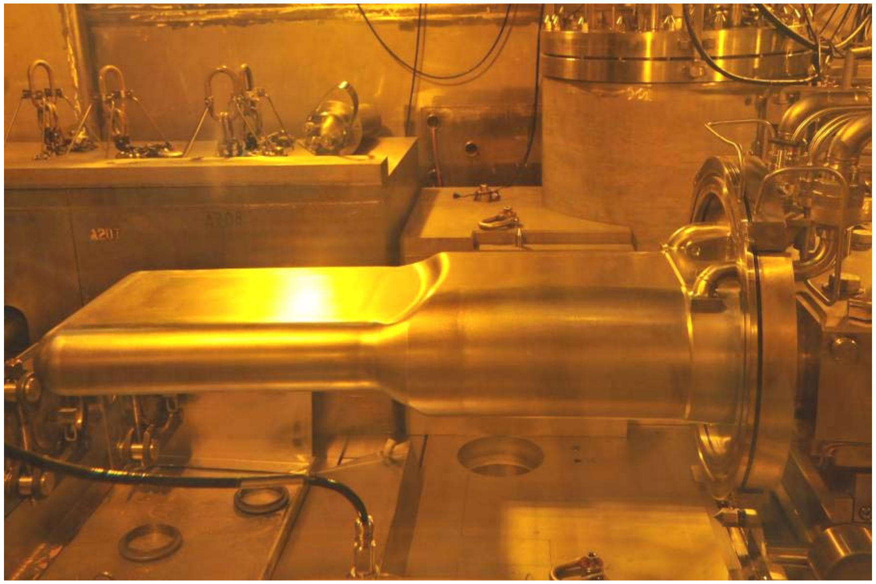
- Imaging system was successful
- Light intensity decreases as a function of time
- Lasts as long as the target, but better understanding is desired

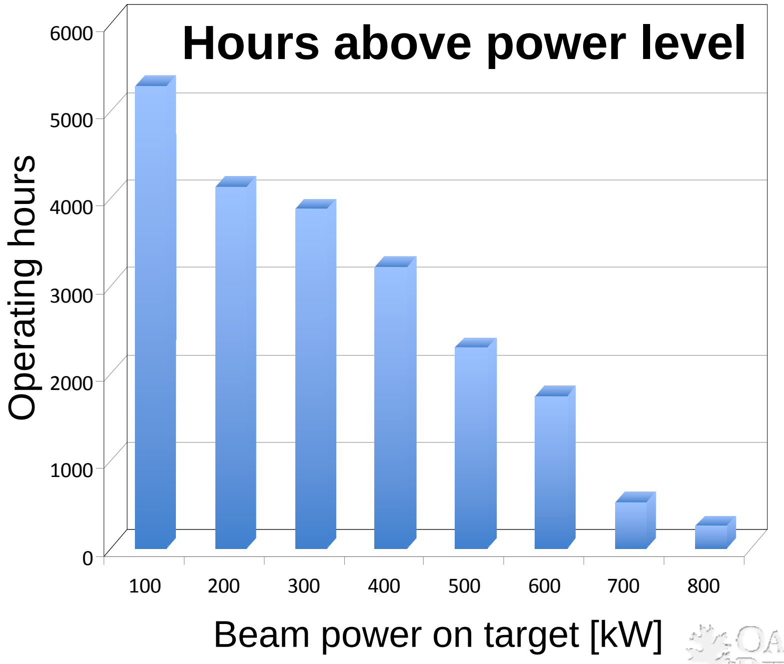




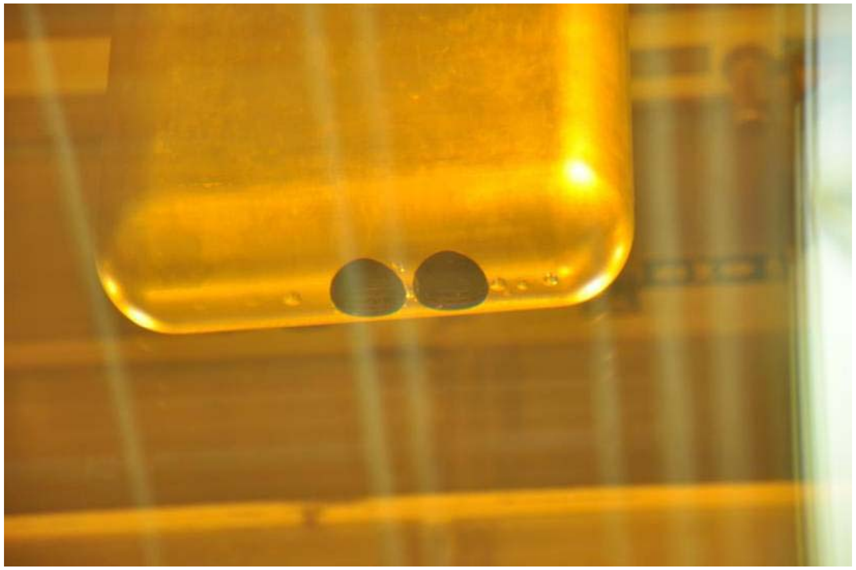
Original target module was replaced in July 2009 because of radiation damage

- Exceeded dpa goal of 5 dpa (reached ~ 8 dpa), but we still do not know how long the target will last at high power
- Exterior appearance is as new
- Boroscope examination completed
  - Camera light died in ~40 seconds; surface dark and textured (coated with Hg?)
- Samples cut from target nose November 5th





Target Sampling

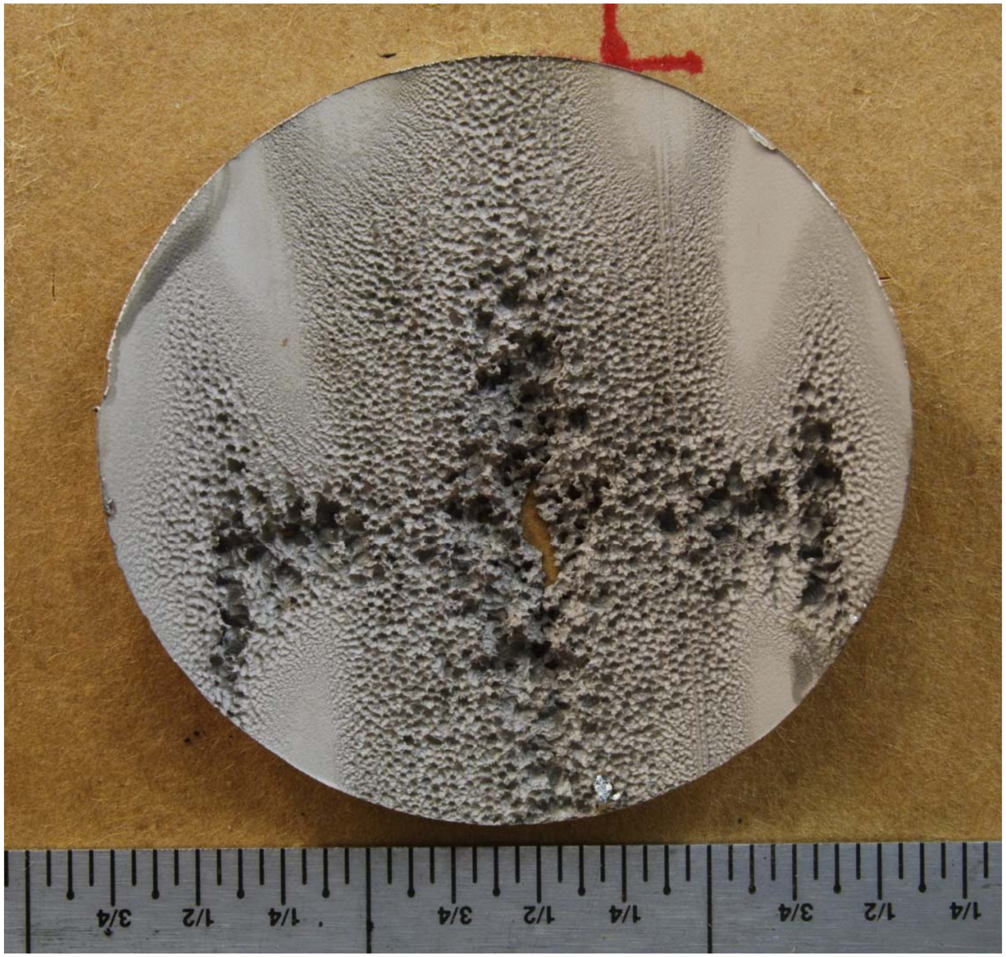


•Target after sampling
•Right of center shows slightly higher peaking than left on imaging system

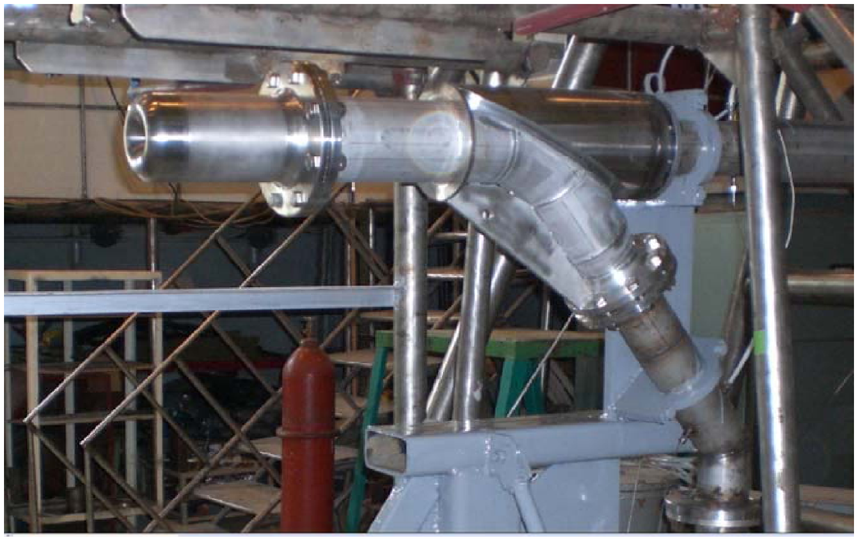
Target in Position

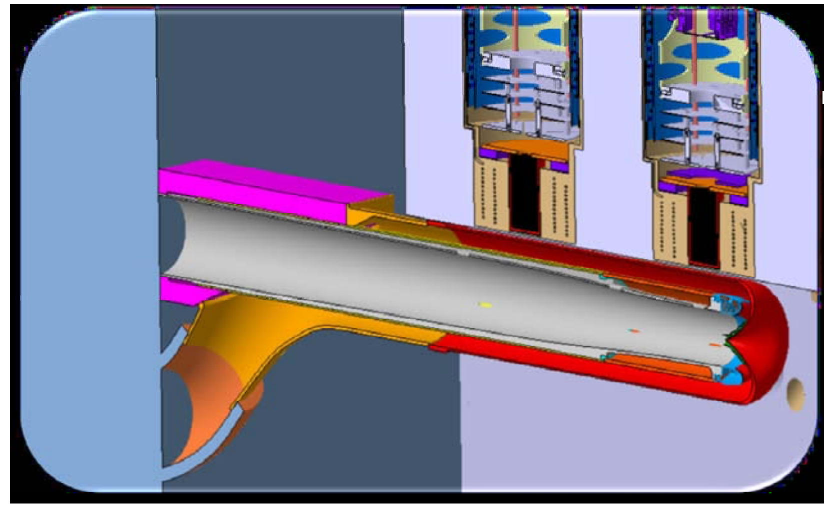
PIE of the first target vessel

- Contract with B&W to clean and test the first target vessel
- Samples are ~10 rem/hr at 1 foot
- Inner target vessel sample is badly pitted due to cavitation damage erosion
- Where is the vessel material going?



EURISOL 4 MW Mercury target*





Off-line test in Hg loop at Institute of
Physics University of Latvia (IPUL)
Mats Lindroos

*Cyril. Kharoua@esss.se / Workshop on Applications of High Intensity Proton Accelerators
October 19-21, 2009 Fermi
National Accelerator Laboratory, Batavia, IL, USA

Target Window Design

- The design of the target window for high power densities on the order of 1 MW/liter will be very challenging
  - SNS @ 2 MW with .25 A/m^2 and 1 GeV had peak heating of ~ .8 MW/liter
  - 316 LN window needed to be ~ 1.5 mm to limit thermal stress
- EURISOL found their window design margins less then desired
- Windowless solutions in principal would allow higher power densities
  - MYRRHA has investigated for ~ 10 years and considers it to be promising
  - EURISOL experimented with transverse flow and obtained stable flows without beam
  - Argonne National Laboratory experiments with lithium films under electron beam heating were promising for high power densities

RACE Project was initiated at Idaho State University in July 2003

- Examine coupling of accelerators and targets to subcritical reactor systems for developing transmutation technology
- Use inexpensive, compact, transportable electron linear accelerators (linacs)
  - 20-25 MeV
  - heavy targets (e.g. lead, tungsten, or uranium)
  - bremsstrahlung photons generate neutrons
  - ~10^{12} n/s/kWe of 25 MeV electrons

RACE slides from project director Denis Beller

Initial RACE Project Plans

- Phase I (ISU) '03-'04
  - Purpose: develop instrumentation and experience for Phase II
- Phase II (UT-Austin) '05
  - TRIGA coupled ADS
- Phase III (Texas A&M) '06
  - Possibly with used core in a purpose-built configuration
  - Cancelled

RACE Progress

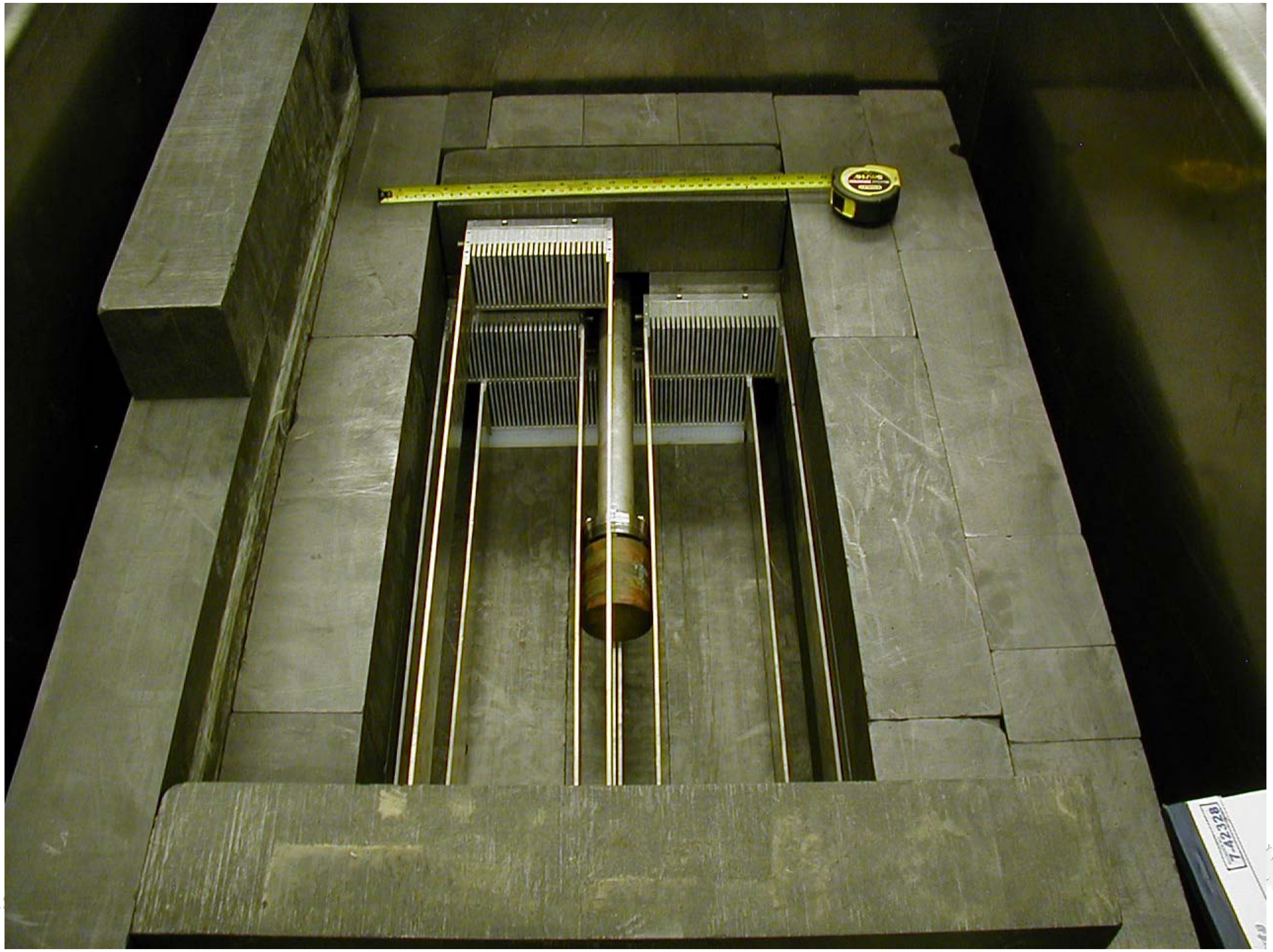
- ISU RACE
  - 2003-2005 design, NRC licensing, and low multiplication testing
  - First full-core loading Dec ’05
  - ADS tests Dec ’05 through Oct. ’06
- Texas RACE
  - Initial experiments at UT-Austin in ’05
  - Longer campaign Jan-Mar ’06
  - TRIGA Returned to normal critical operations Mar 31, ’06
  - Several papers in AccApp’07

ISU RACE
subcritical assembly and accelerator

ISU-IAC Subcritical Assembly

- 150 U-Al fuel plates, 0.08” x 3” x 26”, Al-clad U-Al, 20% enriched,
- 3 horizontal rows, 6 mm spacing
- Accelerator target in center
- RG graphite reflector (8-12”)
- k_{eff} ~0.93 to 0.94 (per ideal MCNPX)
  - ➔Multiplication about 10
- Peak instantaneous flux:
  ~ 10^{13} - 10^{14} n/cm^2/s in the fuel

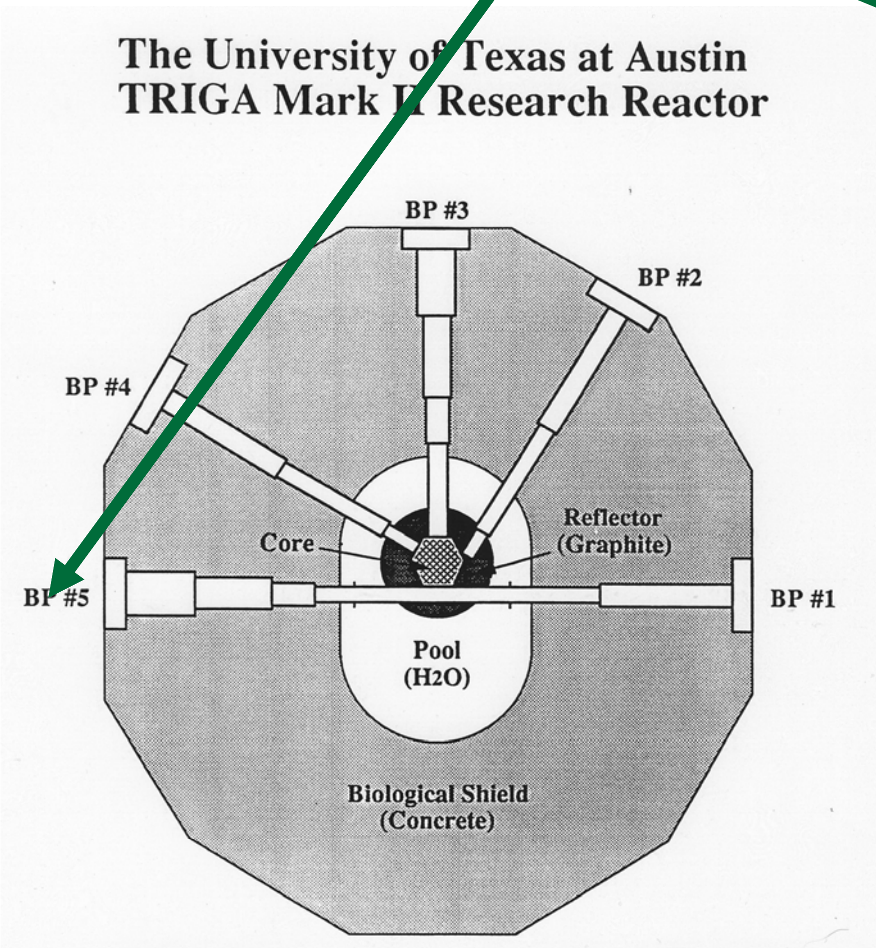
RACE fuel trays (without fuel) and target inside the graphite reflector

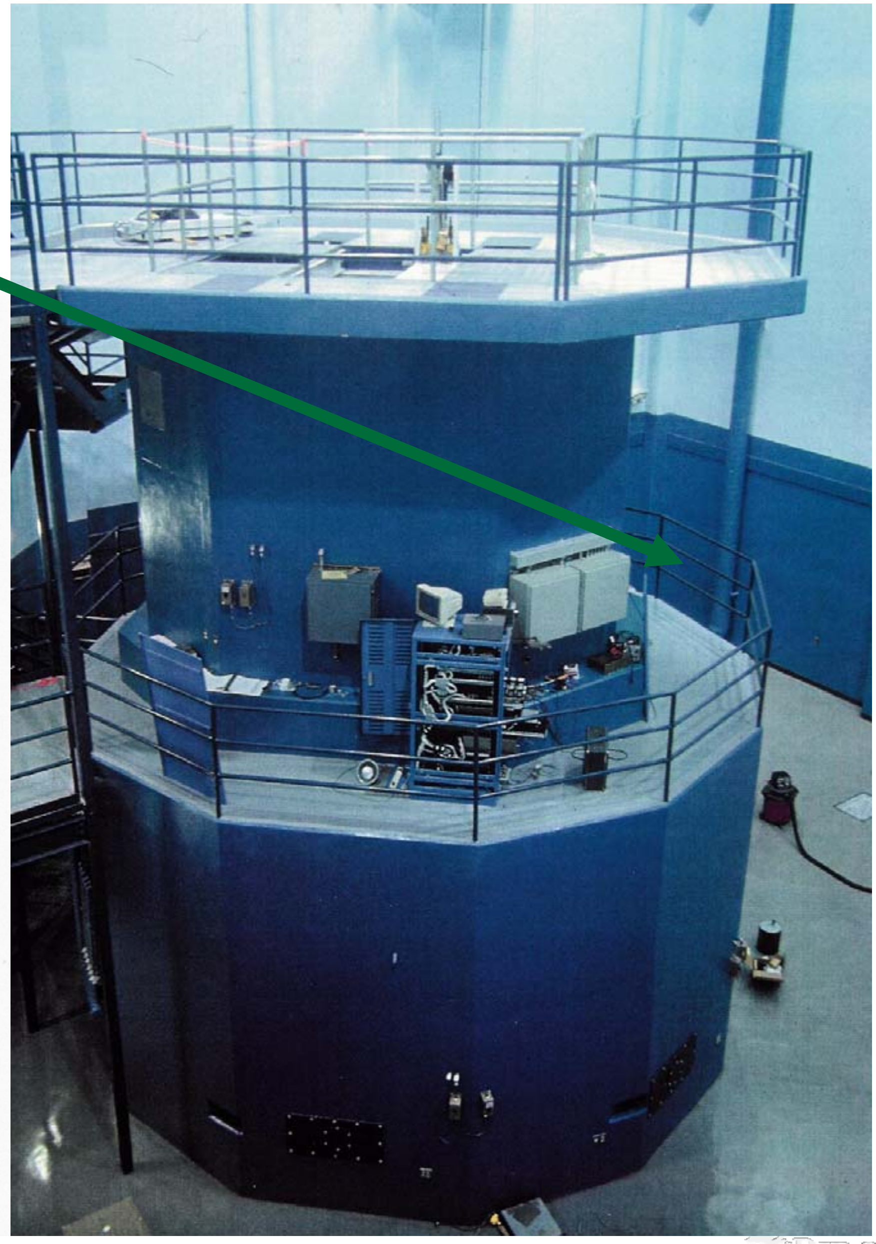


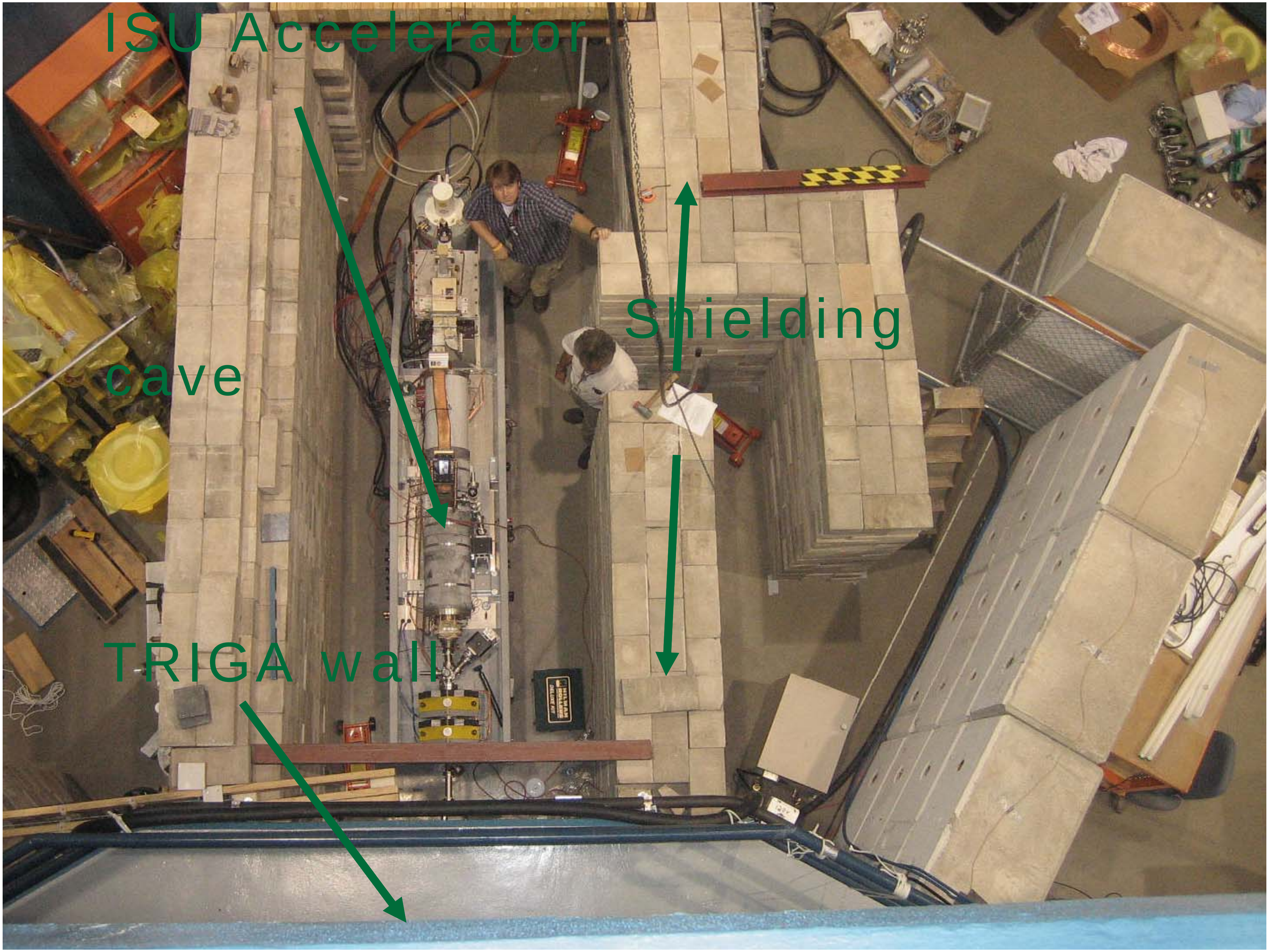
ISU-IAC RACE target

- W-Cu; 2 3/4” dia. X 3.5” long
- MCNPX: ~10^{12} neutrons/s/kWe
- Also a prompt, strong high-energy gamma ray signal

U Texas RACE accelerator location





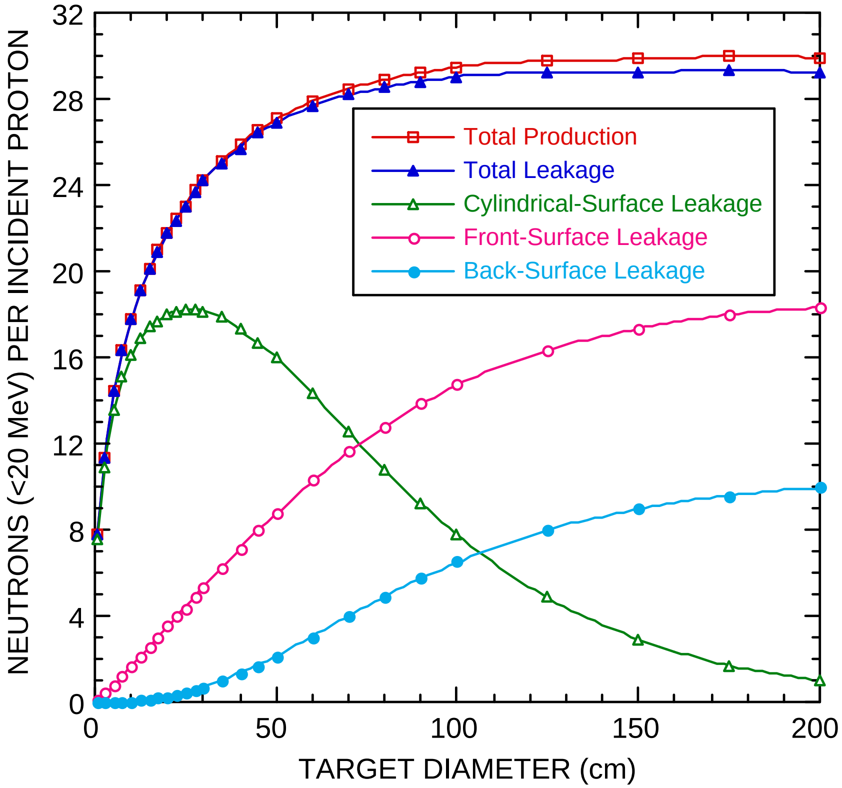

ISU Accelerator
cave
Shielding
TRIGA wall

RACE Accomplishments

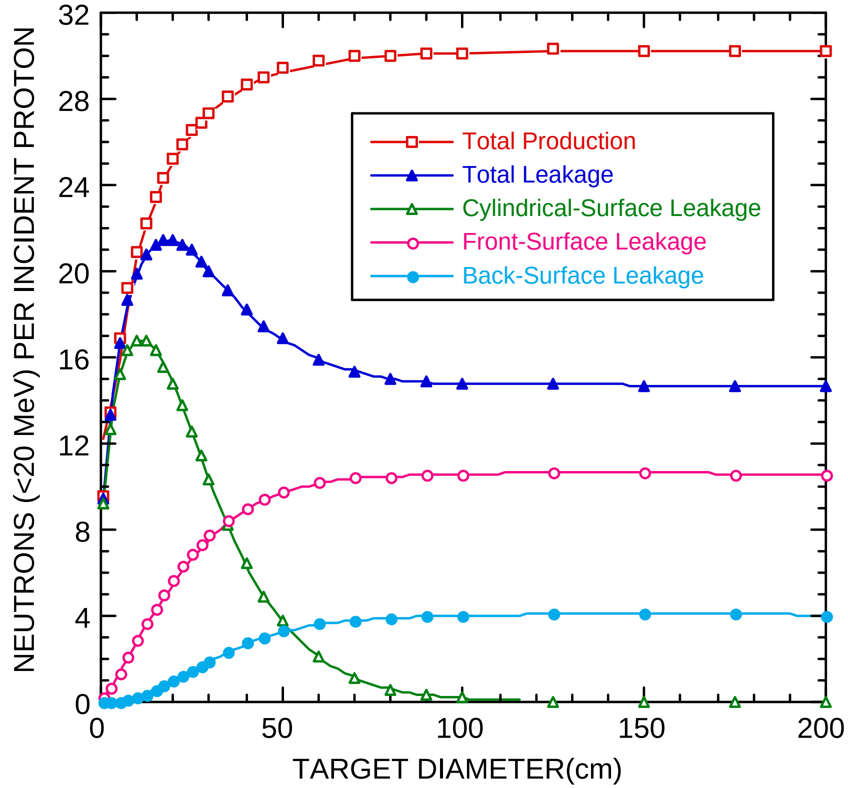
- Licensed, constructed, and conducted ADS experiments
- Five ADS Experiments Workshops (3 were international)
- RACE-ECATS collaboration
  - Target design
  - T-H feedback evaluation
- Education of students at ISU, UT-Austin, U Mich., Texas A&M, and UNLV

Neutronic Performance of Lead and Tungsten Targets

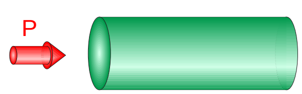
(Stopping-length targets bombarded on axis by 1-GeV protons)



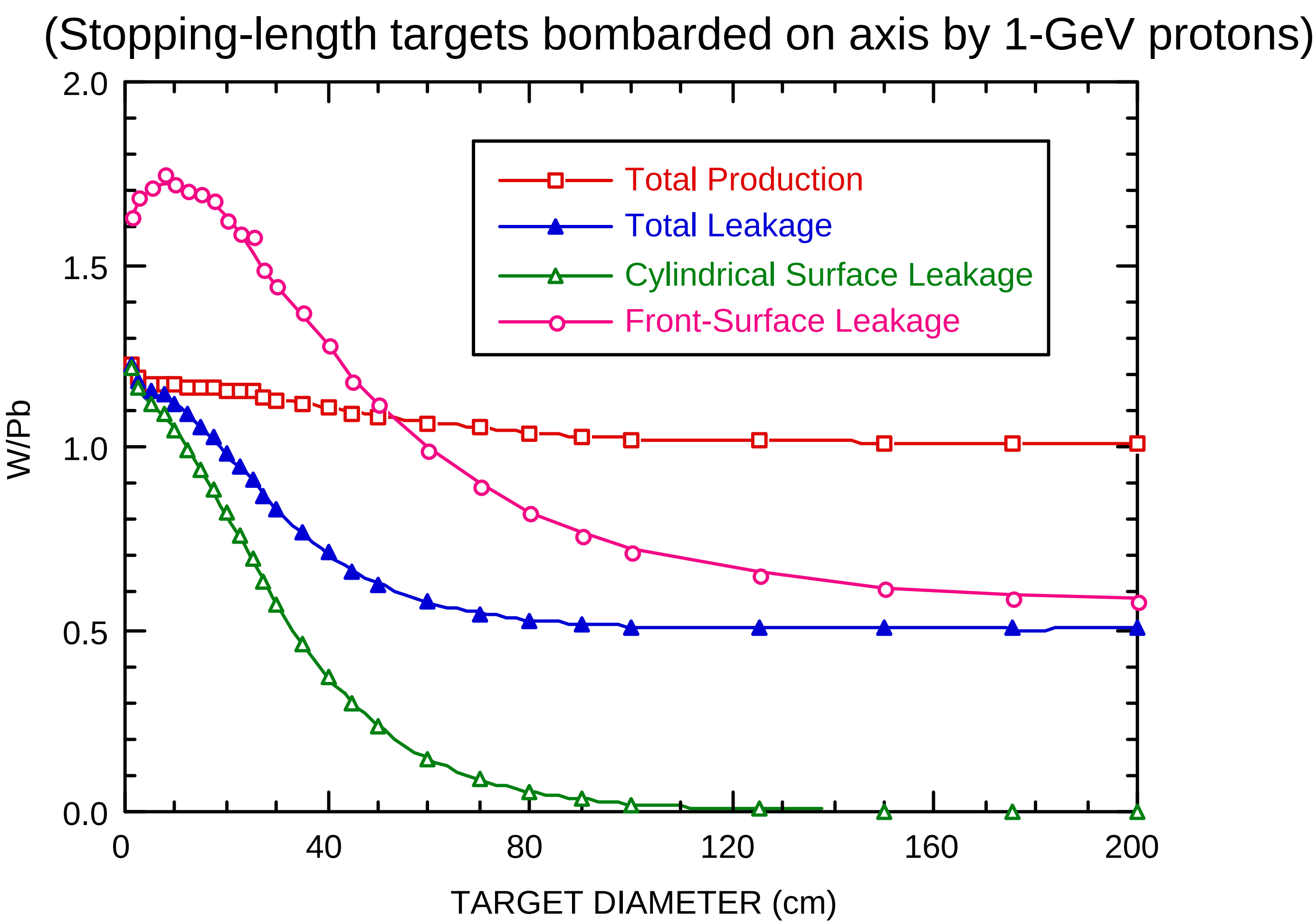
55-cm-long Natural Lead

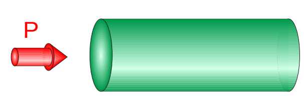


30-cm-long Natural Tungsten

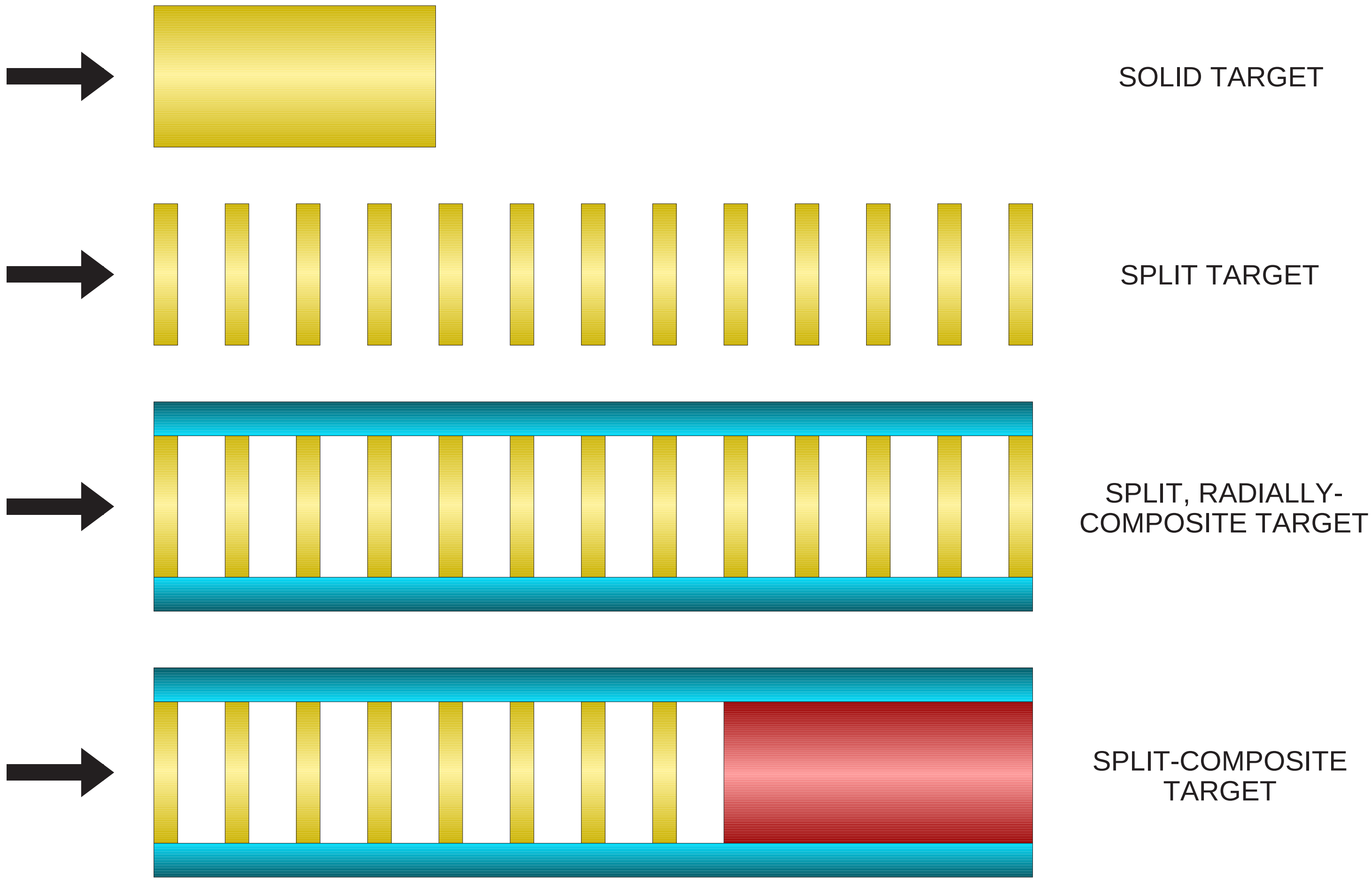


Tungsten Target Performance Relative to Lead



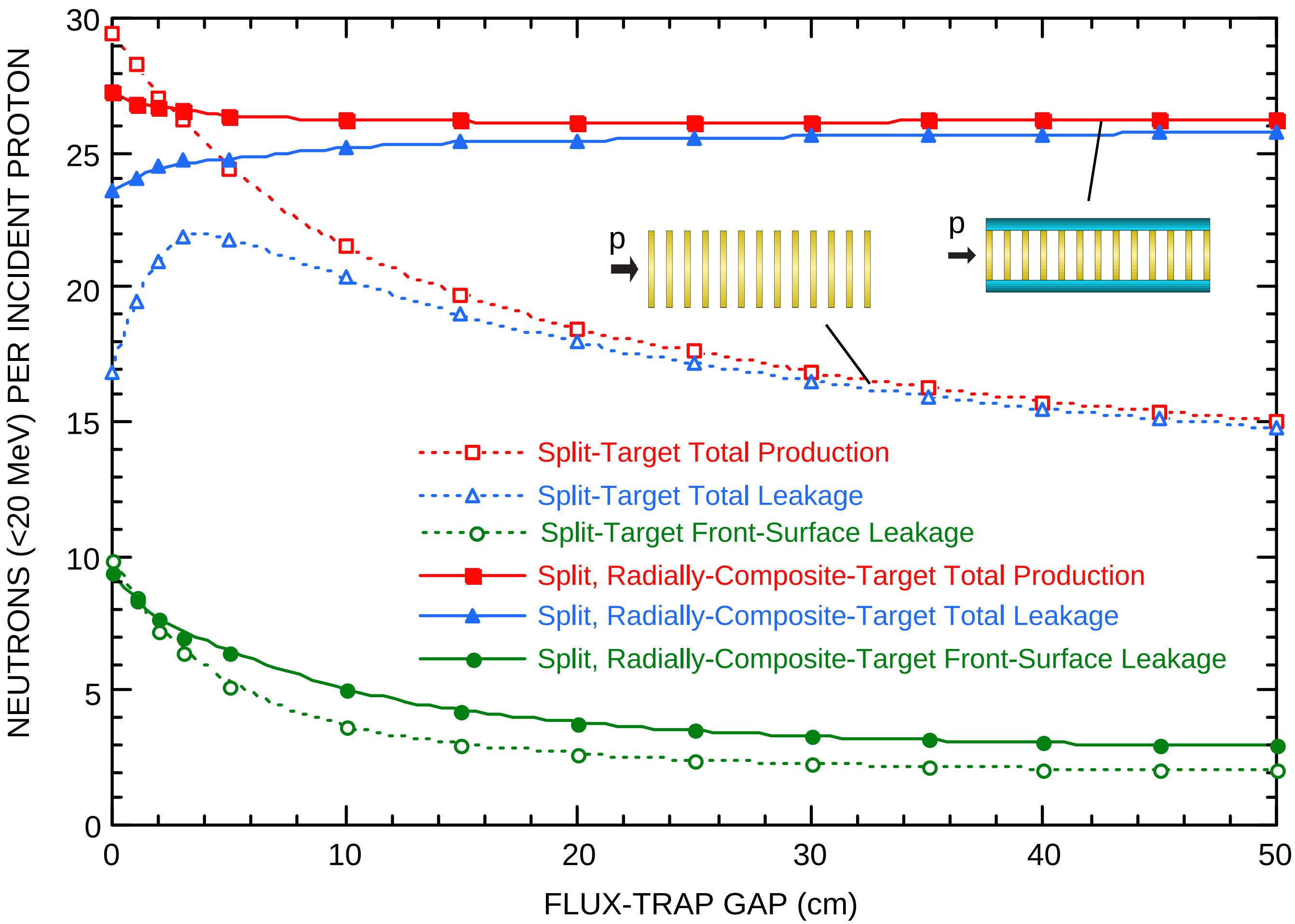


Basic Target Concepts



Neutronic Performance of a Split Target and a Split, Radially-Composite Target

(50-cm-dia, stopping-length targets bombarded on axis by 1-GeV protons)



Summary

- Discussed a few of the accelerator neutron sources and what we could learn from them
  - 3 or 4-MW targets appear to be straightforward
    - Both liquid (long pulse or CW) and solid rotating
  - Radiation damage data exists from LANL and PSI
    - AFCI handbook and papers
    - Watch for additional results
  - Code verification and validation experiments have been completed
    - Expensive – only do what needs to be done
  - Target imaging systems have been designed and tested
  - Po handling experience exists
    - Learn from or collaboration?

Summary (cont.)

- Small coupling experiments were successful in the past
  - Good for the university/students, and good for gaining experience
  - What could be done in this mode now?
- Detailed source design could lead to a target design that is easier to engineer for a demonstration experiment
  - Has it been considered?